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"SCIENTIFIC NOTES

(PROBLEMS OF CYBERNETICS)"

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FOREWORD

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"SCIENTIFIC NOTES (PROBLEMS OF CYBERNETICS)"

[Following is the translation of an article by S. N. Braynes, A. V. Napalkov, and V.B. Svechinskiy, entitled "Uchenyye Zapiski" (Problemy Neyrokibernetiki), (English version above), Moscow, 1959, pages 1-109.]

NOTE: In order to expedite its issuance, this publication has been printed directly from the translator's typescript, after a minimum of retouching, cropping and make-up.

This translation has been printed on one side only because the available mimeo paper stock was unsuitable for standard two-side impressions.

TABLE OF CONTENTS

Chapter VI. Simulation of the Learning Process

NOTE

The book is devoted to the problems of cybernetics. It discusses the laws governing the processing of information and control in living organisms. An exposition is presented of experimental investigations that have detected algorithms at the basis of the brain's functioning as a highly developed self-organizing system.

The simulation method was used for study of problems of neurocybernetics.

The book is directed to scientific workers in the fields of physiology, pathophysiology, medicine, and technical cybernetics and allied areas. It may be of interest to a wide circle of readers interested in cybernetics.

INTRODUCTION

Cybernetics is concerned with study of two basic categories of systems: man-made radio-electronic systems (cybernetic machines) and systems which exist in nature and have appeared in the process of evolutionary development of the organic universe (living organisms).

In these two categories of systems we can detect a certain definite common group of qualitative relationships and phenomena related to the processing of information and control; these result from the functioning of complex systems consisting of a large number of elements which are interconnected and influence one another in special ways.

The occurrence of these common qualitative relationships does not, of course, mean that it is possi-

ble to reduce the laws of operation of the brain to those of a machine.

The approaches to study of the two categories outlined here must differ in accordance with their natures.

In studying cybernetic machines, man is dealing with creations of his own hands, and he obtains, as a result, broad opportunities for analytical study of the laws of operation of these systems. The experimenter can resolve those systems and their sections into their separate components and study the sections in isolation. He can study the operation of the separate elements of which these cybernetic systems are composed.

Investigation of the systems of living organisms does not admit of these methods of analysis. Moreover, the systems operating in living organisms and the principles and mechanisms that are manifested are so complex that it has been impossible to this day to simulate them with machines.

The study of these phenomena is of great interest for cybernetics.

This gives rise to the special nature of studies of living organisms, and that of the brain in particular. These investigations embrace two closely-related problems.

a) Studies of the brain may bring to light important theoretical relationships governing the operation of complex control systems, and these may be of great significance for the development of theoretical cybernetics. Qualitative laws and phenomena discovered in study of the brain's operation may be of use in the creation of new cybernetic machines.

b) The second problem relates to the use of the achievements of cybernetics for study of the physiological processes at the basis of the brain's operation. The study of the general relationships and principles in the functioning of systems which has been based on the creation and analysis of radio-electronic models (cybernetic machines) may be of significance for the study of vital problems of physiology. From this we go on to discover new possibilities for study of the complex forms of information processing in the various divisions of the nervous system, which, needless to say, is of great interest for the solution of a number of pressing biological and medical problems.

Thus, a specific array of problems related to study of the brain defines itself. It differs to a significant degree from both technical cybernetics and the problems of recent physiological investigations,

with respect to both the nature of the problems inherent to this field and the specifics of the methods of investigation used. It is this that has furnished the basis for the resolution of neurocybernetics as a specific field of study.

There no longer exists any doubt that cybernetics may prove of great value for physiology. However, the concrete aspects of the reciprocal relationship between cybernetics and physiology remain unclear in many respects.

Although the present volume does not pretend to offer a solution to these pressing and complex problems, it does attempt to indicate some of the possibilities, using as examples a series of problems which arise in study of the brain.

The work which we thus submit for the reader's attention is not a definitive work in the field of neurocybernetics and makes no pretense to exhaustive exposition of the essence of the problems being attacked by this science. It is merely an attempt to mark out ways to the solution of certain problems which arise in this direction.

The problem to which this study is devoted is a new one. The natural result is that many of the ques-

tions in the book are offered as material for discussion and in the hope that further consideration will result in refinement or even in essential changes in the viewpoints which we advance.

It is our pleasure to express our profound gratitude to Academician A.I. Berg, Professor E. Ya. Kol'man, and Professor V. S. Novikov for numerous instances of valuable counsel which were observed in writing the book.

CHAPTER I

CYBERNETICS AND PHYSIOLOGY

a) The Object of Investigation

N. Wiener /23/ has defined cybernetics as the science concerned with processes of control and communication in living organisms and machines.

A certain tendency toward expansion of the content of the term "cybernetics" as given by Wiener has recently been noted. In particular, it has been emphasized /52, 59/ that cybernetics is related to studies of the laws of information processing in various systems. A.A. Lyapunov /40/ indicates in his theoretical paper that the basic problem which has given rise to the appearance of cybernetics is that of mutual relationships between the capabilities of computing machines

and the thought process, while the basic method is that of algorithmic description of the operation of control systems. W. Ross Ashby /60/ asserts that cybernetics may, in fact, be defined as the study of complex systems. He considers that the difficulties obstructing the study of a whole series of scientific problems in the field of physiology--among which he specifically includes study of the physiology of the brain--result from the fact that the investigator encounters the existence and operation of extremely complex systems. The methods used until now to study these systems have not made it possible to obtain complete analyses of their operation.

In the opinion of Ashby /60/, science has, during the last two centuries, studied the most complex systems of interrelated phenomena existing in nature on the principle of "varying one factor at a time."

Using special experimental techniques, the most complex systems of phenomena have been artificially dismembered into their component parts--into simpler elementary processes--which have been studied in isolation, independently of one another. We know, for example, that to study the highly complex systems of chemical processes which unfold in an organism it be-

comes necessary to sever individual chemical reactions from the over-all system by one method or another. These reactions are then studied in isolation in test tubes under precise experimental conditions. Thereafter, all the experimental data outlined in different experiments and by different investigators are added together and the result used as a basis for construction of an over-all picture of the chemical process taking place in the organism.

Ashby believes that this approach is justified only in study of simple systems of phenomena. It becomes inapplicable, however, when we pass to study of complex systems.

New phenomena and interrelationships which it is impossible to study by analysis of their simplest components arise in complex systems. This situation, which is directly related to one of the basic tenets of dialectic materialism (the transition from quantity to quality) may be illustrated with the aid of the computing machine as an example. Not one of the elements of which the computer consists is possessed of the remarkable properties which the entire system possesses as a whole (the capability to perform complex calculations, translate from one language to another, play

chess, etc.). All these properties are found to be inherent only to the complex system formed by the elements when they are combined in a special manner (i.e., to the cybernetic machine) to form an integrated whole. The same relationship is observed in study of physiological processes, e.g., in study of the functioning of the brain. The brain represents a complex system of interrelated nervous elements. The individual nerve cells possess relatively simple properties. They may be either in a state of excitation or in one of inhibition. They can either transmit a stimulation impulse or not transmit it. The remarkable properties of the brain (thought, imagination, memory, etc.) arise only in the complex systems formed by elements which are related to one another in a special manner. Thus the study of individual nerve elements or individual groups of nerve elements cannot provide us with an understanding of the basic principles of the brain's operation or the basic capabilities which it possesses, no matter how exact the technique employed. These effects and capabilities arise only in complex systems of interrelated elements.

The study of the principles on which complex systems work and the study of the new processes and phenomena that arise in these systems therefore consti-

tute one of the most important problems which physiology faces in our time.

Cybernetics may, in the opinion of Ashby, be of outstanding significance in the solution of this problem, which is not, of course, insoluble and in the solution of which the development of new techniques of investigation may acquire decisive significance.

Ashby writes: "Cybernetics rejects vaguely intuitive ideas and proceeds to the creation of a rigorous science of the processes and phenomena which arise in the systems." Elsewhere he writes, "Cybernetics gives us the hope of creating effective methods for the study of systems of extreme internal complexity and for their control."

The most important property of cybernetics---the one that enables it to approach the study of this problem---is the fact that it gives a unified complex of concepts and a unified system of ideas for study of the systems which function in cybernetic machines and living organisms.

The approach adopted by Ashby /59/ in which he compares cybernetics with the other sciences and geometry in particular, may be employed to account for this important property of cybernetics.

We know that geometry is a science which treats of the laws inherent to highly diverse phenomena and objects in space. Here it is important to stress that the laws of geometry, which were discovered with the aid of abstract thought, may be applied successfully to bridge-building, to the construction of new buildings, to surveying, and even to the analysis of certain physiological problems. At the basis of this phenomenon, as pointed out by E. Kol'man /34/, we find the unity of the laws of nature--the presence in nature of laws common to different phenomena. It is of no importance for the solution of a certain system of problems whether a given object consists of paper, concrete, earth, iron, or some other substance. What is important is that the object has some definite shape (square, rectangle, etc.).

Thus we find it possible to compare different objects with one another and transfer the laws discovered in the study of one object to another object.

Study of the basic laws of geometry would be extremely difficult if these laws were studied directly through bridge construction or surveying. The fact that the laws of geometry may be studied independently of the objects in which they find direct practical application is of decisive significance. A certain system of

general problems and general relationships appears in study of the complex systems which operate in objects with different physical natures, e.g., in electronic computers and in the various physiological systems.

In studies of the functioning of complex systems consisting of large numbers of singularly related and interacting simple elements, we find a specific group of such relationships. The physical material of which the elements which compose the system in question are in turn composed (proteins, metals, etc.) is unimportant for study of these relationshps. What is important is the kind of influence exerted by certain elements on others, how they interact, and the structural arrangement into which these elements are combined.

The presence of just such a common group of relationships is what makes it possible to transfer the principles and phenomena discerned in the study of one system, e.g., in the study of electronic computers, to another system, e.g., to investigation of the laws which govern the activity of the brain. Many important questions can be answered by study of radio-electronic systems during study of the processes unfolding in the various cybernetic systems. These (radio-electronic) systems are highly convenient for study of a whole series

of phenomena. Owing to the possibility of using this method, we have great new prospects for study of a number of theoretical problems related to the operation of complex systems of processes---a circumstance which may be of decisive significance for analysis of the operation of the brain.

The above principles determine the boundaries within which it is possible to compare the operation of the various systems and, in particular, to compare the operation of cybernetic machines with that of the brain. A group of relationships related to the functioning of systems of interrelated elements in which complex information-processing and control mechanisms are in evidence is common to the operation of the brain and that of cybernetic machines.

At the same time, when we consider the brain from the standpoint of study of the complex biochemical substance-exchange processes which determine the activity of the nervous system---from the standpoint of the laws governing the transfer of energy---we detect no similarity between the brain and the cybernetic machine.

It is also necessary to stress that man is a product of social activity, and that the consciousness of the human being is in large part determined by educa-

tion, the conditions of his social environment, and his life experience. Physiological processes determine only the material basis on which the personality of the human develops.

Thus a general comparison of man with a machine is possible only within the narrow framework of study of the relationships manifested in complex systems, and with the same degree of certainty with which we speak of the possibility of applying the general principles of mathematical analysis to the study of the brain's operation.

In speaking of a narrow common group of relationships, however, we do not mean to deprecate the potential of the machine. Thus, for example, we frequently encounter the proposition that the program of operation of **any** machine is fully determined by its designer and cannot be modified in the process of operation. It should be noted that this is not altogether true.

Even the automatic device described at the end of the present volume generates its program precisely as a result of "study" of the conditions surrounding it, restricted as they may be. But this device is very simple indeed, and it was constructed with the rather modest purpose of simulating certain of the learning

processes of animals.*

Man's understanding of nature, including himself, increases in profundity, and there is no doubt that he will create automatic machines that simulate many of the functions of the brain.

It is frequently stressed in speaking of cybernetics that recognition of analogies in the operation of the cybernetic machines and the brain is important. This tendency seems unjustified to the authors. The word "analogy", it seems to us, does not precisely define the system of interrelationships which prevails in study of these two highly different objects. The question of the justification for comparing the brain and the machine will inevitably arise if the problem is thus stated.

A whole series of special investigations has been devoted to this problem /35,25,4/. We consider it much more correct from the methodological viewpoint to speak of the existence of a certain narrow circle of relationships common to the operation of the brain and the machine: those relationships which are connected to the functioning of complex systems.

*See pages 56-58.

It is a familiar fact that the basic laws of refraction of light are equally useful in study of the eye and in the study and design of various optical instruments.

These laws are common to these two highly dissimilar phenomena. Comparison of the eye and an optical system as regards their other properties and their operating principles would clearly be an error. The same relationship exists in study of the brain and the cybernetic machine.

b) Methods of Investigation

The objects which cybernetics studies are highly diversified. The problems of information processing, control, and communication are common to many systems, living and nonliving, and this naturally makes cybernetics a science closely related to a number of other sciences, such as mathematics, physiology, neurophysiology, and radio electronics.

We are concerned here with one of the divisions of cybernetics---neurocybernetics. This term denotes the study of control, communication, and information-processing mechanisms in living organisms and in automatic devices created by man for simulation purposes.

It is clear from the above that great significance

is attached to simulation of the processes that take place in physiological systems.

We know little about the operation of the brain or about the neurophysiological structure of its cortex. The brain may be represented as a complete cybernetic system, but without appreciation of how it is organized. We may form various hypotheses concerning its structure by simulating isolated functions of the brain with the aid of computers.

The study of cybernetic radio-electronic systems and models opens before the investigator wide prospects for scientific analysis of the phenomena which unfold in complex systems, and particularly for study of control-, information-processing-, and information-coding activities and the like. These prospects are due to the fact that the experimenter can assemble various systems and disassemble them into their parts as he sees fit. It is possible to study the operation of different sections of the machines, design different models, etc. These methods of investigation also enable us to study the interplay of various complex radio-electronic systems with one another. The result is that this method has been related to the significant progress made in the recent development of this science.

On examination of attempts to simulate the functions of the brain, we discern two fundamental directions in which the science is moving. The first path is from the machine to the brain. Attempts are being made to create an artificial, synthetic brain by way of speculative constructions without consideration of the actual structure of the brain--i.e., by abstracting from it. It would seem that even Ashby followed this route in designing his homeostat and describing a "thought-capacity amplifier" system. This course requires a large outlay of time and resources, since it is still based on the trial-and-error method so splendidly embodied by W. Ross Ashby in his homeostat. But this approach furnishes very little information on the organization of the brain.

The other course of investigation is based on study of the brain by physiological methods with the purpose of revealing the general laws governing its activity and using the simulation method from that point on.

Here cybernetics is concerned with complex systems which function in nature and which arose and took shape as a result of the long process of evolution of the organic universe. These systems (the brains of man and the animals), whose operation we can study and describe in general terms, possess a number of properties lacking

in contemporary cybernetic machines. Principles and phenomena which are as yet unknown to science are realized in them. The study of these systems is of very great interest for this reason. But in this case the investigator also comes up against great difficulty in prosecuting his experimental research.

As a rule, those methods which prove applicable to the study of radio-electronic systems cannot be applied to study of biological systems, and to study of the brain in particular. The problem which the foreign literature refers to as the "black box" has arisen. Its essence consists in the fact that in the course of an investigation, man may apply a certain disturbance to the system that he is studying and take into account the responses with which the system reacts to these disturbances. In the course of the experiment he cannot directly see the processes occurring in the brain and cannot establish how the nerve cells that participate in this work of the brain are connected to one another.

Physiological investigation may lead to the recognition of a number of important properties of the phenomena under study and to the formation of hypotheses concerning the nature of the physiological mechanisms underlying them. This hypothesis may be created on the

basis of all the information at our disposal in the fields of cybernetics and theoretical neurology.

The next stage in the investigation should be the creation of the corresponding cybernetic radio-electronic model. The realization and study of this model can provide verification of the hypothesis advanced and detection of its inadequacies and errors. Then a plan can be outlined for a new series of physiological experiments which may lead to the creation of a new hypothesis or refinement of the old one.

Thus this method should incorporate a series of successive phases, some of which are related to experiments with animals and others to the creation of cybernetic simulators.

The creation of experimental models may be of great value for the recognition and precise definition of the problems astride the road to the investigation of physiological processes.

We have been constantly impressed in our work with the fact that in creating a cybernetic radio-electronic model of one or another physiological phenomenon we invariably encounter a large number of new problems that necessitate conducting whole series of new physiological experiments.

Thus the second route—that from "brain to machine"—evidently offers greater possibilities for study of the brain.

c) The Role and Position of Cybernetics in a System of Physiological Investigations

The difficulty of studying physiological processes is often due to the investigator's encountering complex interactions among a large number of physiological processes which unfold simultaneously and influence each other reciprocally. As an example, we might note the complex system of physiological processes that unfolds under conditions of intensive muscular activity of an organism in the alimentary canal after ingestion of food, etc. The basic method of investigation in this case consists in attempts on the part of the investigator somehow to isolate some single process from the complex system with a view to studying this phenomenon under precise experimental conditions. Methods of investigating isolated organs or parts of organs (e.g., neuromuscular preparations) are widely used.

The isolated chemical reactions are studied in test tubes. Then a second stage of the investigation, in which the investigator attempts to unify all of the independently-studied processes into an integrated system

and visualize the entire integrated complex picture which arises on interaction of these processes, becomes necessary. This stage of the investigation is highly exacting and difficult, since entirely new phenomena and relationships which it is difficult to predict on the basis of study of the isolated organs and reactions usually arise in the course of the interaction of the various physiological processes (as studied in isolation).

The different processes influence one another. The emergence of one process may interrupt the course of another or, conversely, intensify it; here the influence of one process on the other may be determined by the phase in which the influence is exerted, and, consequently, depend on changes occurring in short intervals of time.

Finally, the emergence of a new process may direct the course of another in an entirely different direction.

For this reason, special techniques of investigation involving the creation of certain schematic constructions on paper, using certain symbols to represent the over-all picture of the physiological processes, acquire decisive significance in the process of the scientific investigation. It becomes possible by this method to form a clear concept of the flow of the processes in the organism, to

draw a series of important conclusions regarding the results of their interaction, and to map out a plan for new experiments.

However, this problem cannot be fully solved by the methods of analytical investigation.

The method of studying the "whole organism" acquires great significance in this connection. As we know, the researches of I. P. Pavlov and his students /54,2,5,19,20/ were of decisive significance in the development of this method.

The basic principles of this method involve the investigator's application of various sets of disturbances to the organism of the healthy animal in the course of the experiment (he introduces new substances, applies signal complexes, etc.). The complex responses of the organism to the disturbances produced are observed during the experiment (blood-pressure levels are measured, pulse taken, motor-reflex reactions recorded, salivary secretion noted, etc.). In this, as a rule, the investigator cannot conduct direct observation of the physiological processes under way inside the organism. In his detailed discussion of these methods, W. Ross Ashby /60/ uses the term "black box" with the intent to stress that during the investigation the investigator knows only the

general character of the ensemble of disturbances being applied to the organism, and cannot follow the unfolding of the physiological processes directly. It is impossible to draw direct conclusions as to the character of the physiological mechanisms on the basis of these experiments. In this connection, frequent recourse is taken to the construction of working hypotheses. The investigator usually takes up pencil and paper to create a definite hypothetical flow scheme of the nervous processes. In drawing up this hypothesis he makes use of the sum total of information gained previously on the basis of study of the physiology of the isolated organs, as well as all of the achievements of physics, chemistry, biology, and other disciplines with which he is familiar. It should be stressed that the hypothesis selected does not always proceed directly from the results of experiment. It is the result of creative generalization of all available scientific knowledge at the disposal of the scientist, the result of a certain creative process in which the use of various analogies and parallels sometimes plays a major role. Hypotheses frequently appear as a result of chance "brainstorms" of the investigator.

In analyzing the methods of investigation described above, we should devote special attention to the stage

of the investigation in which the hypothesis is created. This phase is extremely important, since the direction of the entire subsequent experimental procedure depends on it. Major difficulties are frequently encountered in the realization of this stage, and it is here that the relationship of physiology to the attainments of other sciences becomes most clearly evident. This problem is of importance for us because it is precisely in this phase that the role of cybernetics in the over-all complex of physiological investigations may show its value.

It must be stressed that the formulation of a correct hypothesis in physiology, which opens broad avenues to further experimental research, is invariably based on attainments in the corresponding branches of other sciences. The development of physiology has always been intimately dependent upon the attainments of physics, chemistry, and the progress of technical thought. Scientists might to this day be arguing over the significance of expansion and contraction of the pupil, changes in the crystalline lens, and other characteristics of the operation of the eye had the laws of refraction of light in lenses not been known. The work of the heart became understood as a result of the fact that apparatus working on the same principle as

the heart already existed in technology. The discovery of the phenomena of radar made it possible to understand the mechanisms which permit bats to fly in total darkness without colliding with obstacles.

Apart from these difficulties, the study of certain physiological mechanisms is considerably impeded by the fact that the physical phenomena at their roots have not yet been studied. It is such a situation which we encounter in the case of study of the brain.

The lack of the corresponding information in the fields of physics, chemistry, and technology makes it impossible to construct a hypothesis that will guarantee the correct direction of the experimental physiological investigations.

The analysis furnished above defines the place of cybernetics in the system of physiological investigations. It creates the theoretical premises on which we may formulate valid hypotheses and concepts of the nature of the physiological mechanisms; as we have noted, it thereby determines the direction of further physiological experimentation to a considerable degree, providing for selection of the most valid and promising paths of investigation. We must concur with Ashby /59/ that the lack of progress in the study of a whole series of

physiological problems has been due to lack of knowledge of the general principles and relationships governing the functioning of complex systems. Cybernetics formulates such a theory and thereby creates new premises for the successful development of many departments of physiology.

We must point out the erroneous nature of the idea that cybernetics may replace or "render unnecessary" the physiological methods of investigation, and also of the assertion that cybernetics alone, without benefit of physiological experimentation, can solve biological problems (and the problem of the brain in particular). It does not eliminate the necessity of using existing methods of experimental physiological investigation, but can only make these methods more effective.

In concluding this section, attention should be devoted to certain problems related to the use of simulation. It is still necessary at the present time to listen to objections to the use of this approach in physiology. The simulation method has nevertheless been used in various fields of science and technology for a long time. Prior to building a new machine or instrument or designing a new technological installation, engineers very frequently construct models of their future crea-

tions. The model is usually not an exact copy of the installation being designed. It may be built with other materials, or have totally different dimensions. In spite of this, certain important relationships which are of great importance to the work on the project may be discovered in study of such a model.

Simulation is also employed in chemistry and physics. Indeed, even the structural formula of a chemical compound is already a kind of model in a certain sense. The individual atoms and their bonds are denoted in this model with the aid of defined symbols.

Models may be used to form a conception of the course of complex chemical reactions. W. Ross Ashby /60/ presents an interesting example illustrating the advantages of this method. He refers to the fact that using the pencil-and-paper simulation method, Leverrier and Adams discovered the new planet Neptune in a few months' time, while the solution of this problem by direct telescopic searches for the planet would have required the scientists' entire lifetimes.

But scientists also use such methods of simulation in studies of physiological and biochemical processes. As we have said, scientists frequently come up against a complex pattern of interactions between numerous physio-

logical processes in their study of living organisms. These processes unfold concurrently and show reciprocal influences on one another.

One of the most critical stages of a physiological investigation is the creation of definite schemes on paper. The formulation of such schemes may be of great significance in the process of the scientific investigation. In this way, the experimenter can form a complete conception of the complex phenomena under study, generalizing it to include information obtained at different times and by different methods. On the basis of analysis of the scheme, he may create new working hypotheses and mark out new series of physiological experiments.

The method by which such schemes are formulated is essentially the simulation method.

Techniques have recently been developed which permit the creation of dynamic models. Models of various physiological processes and phenomena can be created in modern cybernetic machines. The use of such models could play a major role in study of a whole series of problems of medicine and physiology. Active Member of the Academy of Medical Sciences of the USSR V. V. Parin has noted the significance of this direction for the

development of medical science.

Thus the question as to whether it is necessary to use models has already been answered in the practice of scientific research. At the present time, it seems to us that another question---that of whether we can employ the contemporary achievements of technology to perfect the actual methods used in the creation of models---has acquired more pressing significance.

As has been noted by the eminent Soviet scientist A. I. Berg /10,11/, recent attainments of radio electronics are opening broad possibilities in this respect.

It must be stressed at the same time that the simulation method cannot in itself solve physiological problems. It acquires major significance only in cases where it is used in close combination with the physiological methods of investigation.

The creation of this or that electronic model cannot in itself serve as proof that just such a system of nerve elements exists in the brain. It is well known that one and the same external effect can be achieved as the result of creating different radio-electronic systems.

Certain rules, the violation of which may result in serious systematic errors, must be observed in design-

ing and studying cybernetic models. It must be stressed that the model (e.g., a conditioned-reflex model) can never achieve identity with the biological system under study; it should only provide an embodiment of the principles for study of which it was created.*

The modern theory of the "isomorphism" of different systems is of great significance in application of the simulation method. The concept of the "isomorphism" phenomenon which is set forth in particular in the books by I. A. Poletayev /52/ and W. Ross Ashby /60/ provides a theoretical basis for understanding the complex interrelationships which compound one another in studies of the brain and cybernetic models thereof.

It would be incorrect to suppose that physicists and mathematicians conducting work in the field of cybernetics can solve biological problems by themselves. We have already emphasized that progress can be achieved in the field of physiological study only on combination of the methods of physiological experiment with the methods in wich corresponding models are built. Therefore only when physiologists and biochemists possess the techniques of modern cybernetics and learn to use these methods of investigation creatively in solving

*See pages 56-58

specific problems of physiology and medicine may we expect the decisive turns in the development of the science for which the way has already been prepared by the development of radio electronics.

d) Neurocybernetics and Study of the Brain

Many of the processes taking place in the cerebral cortex have been studied in recent years, but the physiological nature of such basic and characteristic phenomena of the brain as the thought process, memory, etc., remains unknown, although the solution of certain pressing practical problems depends to a considerable degree on progress in the study of these problems.

The brain is a complex system ("assemblage") of nervous elements which are related to and influence each other in a special manner. The most complex patterns of interaction of a very large number of nerve cells arise during the operation of the brain. A mosaic of stimulated and inhibited elements is formed in the process.

It has recently become clear that the solution of a series of pressing problems related to study of the brain is to be sought in study of the systems ("constructions") formed by the nerve cells and the physiological processes which take place in these constructions.

It is known that individual nerve elements do not possess the remarkable properties (thought, imagination, etc.) that are characteristic of the brain as a whole. These phenomena arise only in systems that integrate many thousands of nervous elements. Here we come up against the state of affairs which is more clearly manifested in the operation of computing machines. As we have said, each of the elements of the computer, e.g., a radio tube, possesses relatively simple properties. Only in systems whose composition unifies a great number of singularly interrelated elements do the remarkable properties inherent to modern electronic computers make their appearance--the ability to play chess, translate from one language to another, perform complex calculations, etc.

Thus the problems of study of the brain are found to be closely related to analysis of the operation of systems of interrelated elements.

The difficulties encountered by the physiology and pathophysiology of the brain have been related in large part to the lack of systematic methods which would permit an approach to the solution of this problem. This important circumstance--the significance of which has become fully evident only recently--is often disregarded.

In the past, physiologists have made numerous attempts to approach the study of the brain using the methods developed and justified in study of the internal organs. These methods involved irritation of isolated zones of the brain by electric current and various pharmacological agents, removal of various areas of the brain and the study of the bioelectrical phenomena that appear during the operation of the various nervous elements and groups of elements.

These systematic methods of investigation have made it possible to accumulate a large volume of new and somewhat disjointed factual material characterizing the operation of the brain, but have not led to the discovery of new principles and mechanisms in its operation. The lack of a general theory for the study of complex systems has frequently resulted in the deduction of erroneous conclusions on the basis of experiment. For example, some section of the brain is removed in the course of an experiment. The changes which appear in the behavior of the animal are studied and used as a basis for an inference as to the function borne by the excised section.

This method would be valid if the brain were the mechanical sum of the various nerve centers. Actually,

however, the removal of any section of it may result in changes in the system as a whole, or in inhibition or stimulation of other sections, and the result may be an observable change in the operation of the brain. The same mistake can be made in employing the techniques of irritating isolated sectors of the brain and picking off bioelectrical potentials from the various nerve centers.

Since it was difficult at the time to predict the results which a new experimental technique might produce, the potential in certain methods of investigation was considerably overestimated. It was thought (and this is still maintained by a number of modern physiologists) that it would be sufficient to improve the experimental technique to the point where it was possible to read the biocurrents from a great number of nerve cells, combining this method with that of artificial stimulation of sections of the brain, in order to discover a way to recognition of the basic laws and mechanisms of the brain's operation. This idea diverted the attention of the investigators into an exceptionally laborious and complex channel which, as has become evident in recent years, does not justify the hopes attached to it.

As a result of the emergence of cybernetics, scientists have, in recent years, acquired experience in the study of various types of complex systems. The prospects for study of the brain, as an exceedingly complex system, have improved at the same time. Possibilities for more correct evaluation of the various methods of investigation are being revealed. It becomes clear that the difficulties related to study of the brain are not technical, but fundamental in nature, and that they can be overcome only through methods of studying the brain as a complex integrated functional system. Even the newly-developed methods of investigation involving measurement of the brain's biocurrents with the aid of microelectrodes, with simultaneous recording of the biocurrent-takeoff methods cannot, taken alone, solve the basic problems of the brain's physiology.

Let us imagine a certain ideal case. Suppose that it were possible to make a simultaneous and continuous record of the potentials on all nerve cells of the brain. In this record, the potential of each cell will be registered independently of the others. In this case the experimenter would obviously find himself in the position of a man trying to grasp the principle of a computer from the flickering of the vacuum tubes and

the operation of the relays. Such a problem will obviously prove difficult if the man is unacquainted with the general principles of the operation of systems of this type. Attempts to stimulate isolated elements--which may be compared with the possibility of cutting in individual tubes--lead to the same result. This technique may lead to the discovery of new facts and relationships, but cannot yield knowledge of the basic operating principles of the system.

In presenting for comparison a system consisting of radio-electronic elements, we reasoned that certain principles of the study of complex systems could be illustrated more clearly using this system as an example.

Thus it becomes more and more clearly necessary to use methods of investigation which permit the study of the brain to be approached as that of a complex functional system.

As we know, the development of the objective method of studying higher nervous activity by I. P. Pavlov and his students has been of decisive significance in the study of this problem. The basic principles of this method are quite familiar. It consists essentially in applying certain definite disturbances and different complexes of disturbances (complexes of stimuli) to the

brain in the course of the experiment and studying the responses of the system to these stimuli.

This method may be used to reveal the general rules (algorithms) of the brain's operation as a functional system. It makes it possible to include any complex of signals in the experimental procedure and to take into account precisely both the nature of the set of stimuli and the nature of the animal's complex responses. Thus it opens broad vistas for scientific analysis of the phenomenon under study.

I. P. Pavlov discovered the basic rules which lead to the formation of new conditioned-reflex reactions and to the disappearance (inhibition) of temporary associations formed earlier. These rules are well known.

It must, however, be stressed that the nature of the brain-activity relationships noted in the course of the experiment depends to a major degree on the nature and complexity of the complex of disturbances which the experimenter has applied to the brain in the course of the experiment. When this problem was first studied, a relatively simple form of experiment that enabled us to discern the laws of formation of isolated conditioned reflexes was employed. However, the great significance of I. P. Pavlov's discovery lies in the very fact that

it gives general principles which form a basis for further development of this field of inquiry. Proceeding in the direction of more complicated sets of experimental disturbances, the experimenter has the opportunity to study increasingly complex systems of rules (algorithms) governing the operation of the brain.

In this connection, investigations carried out in recent years in which more complex systems of disturbances have been employed and which have led to the development not of single conditioned reflexes, but complex systems of conditioned-reflex reactions, have acquired great significance /1,12,14,15,19,20,21,37,55/.

The problems of study of the brain are closely related to the group of concepts studied by cybernetics in connection with the "black box" problem. Here it must be noted that we speak in this case of study of a highly complex "black box" which not only shows certain types of response to various signal complexes but can also modify itself under the influence of these signals. This "black box" has a vast number of inputs and outputs in the form of receptor and effector nerve cells, and each of the disturbances entering the central nervous system or going from it to the periphery encompasses a complex system of inputs or outputs.

Broad new prospects for investigation of the brain are unfolding as a result of the recent achievements of cybernetics, and of the development of neurocybernetics in particular. Cybernetics works out methods which permit us to approach the investigation of complex systems and thereby overcomes a series of formidable difficulties in the way of investigations of the brain.

As a science possessing specialized techniques of investigation and having its own range of problems, neurocybernetics cannot embrace all aspects of the brain's operation. In particular, it does not consider the various specific forms taken by the migration of matter and lying at the foundation of the brain's activity; the complex bioelectrical phenomena and processes related to the exchange of matter and energy remain outside its field of vision. The subject-matter of cybernetics is formed chiefly by the complex mechanisms of information processing and control which are at work in the brain. These processes are related to the functioning of complex systems consisting of large numbers of nerve cells related to one another in a special way.

Two basic directions of investigation may be distinguished in studies of the brain. The first is concerned with study of the general relationships (algor-

ithms) of the brain's operation. The second task is study of the physiological mechanisms of its operation.

As we have already said, the first of the problems listed above can be studied successfully on the basis of the methodsworked out by I. P. Pavlov.

The attainments of neurocybernetics are opening new prospects for the investigation of this problem. The development of a general theory of self-organizing control systems makes possible a broader approach to the problem of study of the brain's operation. It becomes possible to consider the complex system of interactions that arise between the brain and the external medium, taking into account not only the influence of various complex of external signals on the brain, but also the changes which the organism introduces into the medium surrounding it. In the study of this problem it is found necessary to use a series of specific methods of investigation, and the simulation method in particular. This problem will be considered in detail in Chapters IV and VI of the present work.

The methods of neurocybernetics are also of great value in study of the second of the problems listed above. The question as to the mechanisms of operation of the brain is one of the most complex of questions.

For a study of this problem it is necessary to describe in greater detail the basic rule (algorithm) of the brain's operation, since without a more or less complete description of the basic principle of operation of the system it is difficult to create productive hypotheses concerning the principle of its internal mechanism. As we have noted, definite results have been obtained in this respect.

The development of a theory of the nerve network is an important achievement of neurocybernetics (the principal points of this theory are set forth in Chapters II and IV).

In the first stages of study of the brain, when the investigator is dealing with relatively simple forms of its activity, physiological analysis of the facts ascertained may be based on consideration of the scheme of the simple reflex arc of a single conditioned reflex. Later, however, in analysis of the phenomena which arise in complex systems of motor conditioned reflexes, this approach is no longer adequate. It becomes necessary to pass on to consideration of nerve networks, systems consisting of very large numbers of interconnected nervous elements, and to consideration of the processes which unfold in these systems. In the course of such an exam-

ination, it is found necessary to use the sum total of information regarding systems of nerve elements which is at the present time at the disposal of the network theory. thus, "the nerve-network theory" which, of course, cannot in itself, in isolation from physiological experiments, lead to conclusions concerning the mechanisms of operation of the brain, can play an important part in the solution of this problem.

As we know, one of the bases of this examination is the assumption that nervous elements may have a certain excitation threshold, with the result that they come into a state of excitation only when several impulses arrive simultaneously at nerve cells. This principle, which has been confirmed as a result of physiological study of the work of nerve cells, enables us to pass to analysis of more complex phenomena. On this basis, we may visualize a nerve network which possesses the capacity to keep track of the number of incoming impulses, to compare different complexes of stimuli with one another, and to detect the moment of coincidence of two signals. One possible structure of the nerve network on the basis of which conditioned-reflex chains are formed is presented in Chapter VI of the present work. Such systems may in fact exist in the brain, so that there is no basis to proceed only

from the system of the simple reflex arc in our theoretical examination of the physiological mechanisms.

It should be noted that although the nerve-network theory seems at first glance to have developed independently of physiological experiment, such a mutual relationship must undoubtedly exist. Experimental demonstration of the existence of new complex forms of the brain's operation poses new problems in the development of the principles underlying the structure of the nerve networks at the foundation of the newly observed properties of the brain's operation.

These problems must be worked out in close combination with physiological experiments on animals. Physiological experiments make it possible to break down such complex phenomena such as, for example, the "concept formation" phenomenon, etc. into their simple components.

The nerve networks can be worked out on the basis of the experimental investigation.

The creation of corresponding radio-electronic models may be of great value in conducting this work. The creation of a model may confirm the validity of the system of presentation which has been worked out.

We encounter the problem of finding ways to dem-

onstrate the identity of the hypotheses advanced on this basis to the specific structures of nervous elements functioning in the brain.

It is possible to work out several nerve-network arrangements which provide similar external forms of the system's operation. It can also be assumed that some other type of structure based on other as yet unknown principles are used in the operation of the brain. Although we acknowledge the difficulty of solving this problem, it should be stressed that it is not insoluble.

Even now, we can outline certain paths to the solution of this problem which have been used successfully in other branches of human knowledge (in chemistry, physics, etc.). This method involves advancing several hypotheses and then designing experiments which will reject one of the hypotheses and confirm another.

1) In studying two or more different nerve-network systems, we may find certain specific conditions under which they will not behave identically. In this case we may set up a special experiment which will show how the brain behaves under given conditions. This experiment will enable us to reject one of the hypotheses and confirm the other. Such a method of investigation is widely used in chemistry when reactions of a com-

pound with other substances are studied in order to confirm a new hypothesis concerning a structural formula.

2) In studying one or another hypothesis regarding the structure of a "nerve network," it may be found possible to predict definite forms of behavior of the given system in new situations. If the experiment confirms the assumptions made and we thus succeed in predicting new phenomena on the basis of the theory, then the theory acquires a right to exist.

3) The possibility of accounting for a large number of previously-described facts usually acquires great significance in confirming the validity of a hypothesis. Quite often, an intuitive conception of a theory as "fully valid" is formed without real direct proof, on the basis of the fact that it explains many observations which had not been explained previously.

4) Various methods of study of the brain involving stimulation of its various sectors, extirpation, the reading of potentials from various sectors, etc., may be used to confirm or discredit various hypotheses. These methods may be of value if they are used to prove or disprove hypotheses which have already been formu-

lated.

5) Study of the morphological structure of the brain as well as analysis of various cases of damaged sectors of the brain in connection with study of functional disturbances may be of great value in the confirmation of a hypothesis.

At the present time the complex pattern of the brain's structure presents a mystery. If a hypothesis were created which accounted for all of the peculiarities of the arrangement and structure of the nerve centers in the brain and the specifics of the functional disturbances which occur when they are damaged, such a hypothesis would obviously be highly valuable and would be regarded as sufficiently authentic.

6) The criterion of practical applicability is the final confirmation of the validity of a theory. If a method of analyzing the activity of the brain which we have described leads to progress in explaining the causes of its illnesses and assists in the solution of certain technical problems then it has obviously acquired a right to exist.

Thus the problem of demonstrating validity of this or that hypothesis is not an insoluble one. At any rate, mention of the difficulty of demonstrating

the validity of hypotheses cannot be taken as a weighty argument against carrying out work in this direction.

e) Neurocybernetics and Pathophysiology

The study of the causes of illnesses and their pathophysiological mechanisms is closely related to study of complex systems in which control and information-processing mechanisms are in evidence. Here we consider not only the functioning of the systems in their normal state, but also the various forms of disturbance and deviation of the control and regulation processes. As a result of this, neurocybernetics has recently required central significance for the study of pathophysiological problems.

Methods of investigation involving dismemberment of complex processes into their component parts and the application of disturbances to these isolated elements of the system have been used extensively in the study of pathological phenomena, just as in physiology. Here the fundamental logic behind the investigation frequently reduces to the following: If the removal of an organ, the severing of a nerve trunk, or the artificial inhibition of a process has resulted in the disappearance of the symptoms of the illness, it is concluded that the eliminated factor was the cause of the

illness in question. On the other hand, if the introduction of a substance, the stimulation of a nerve, or the transplantation of an organ has resulted in the appearance of symptoms of an illness, then this could be regarded as a basis for the advancement of a new hypothesis concerning the causes and mechanisms of development of the pathological state in question.

Numerous hypotheses concerning the causes of illnesses have been formulated on the basis of such information and new methods of treatment devised. For example, numerous hypotheses have been advanced on the causes of hypertonic disease, which are related to disturbances in the operation of the kidneys and depressor nerves, humoral imbalance in the composition of the blood, disturbance of centers in the brain, etc. The corresponding methods of treatment focused on these organs (for example, removal of sympathetic ganglia) have been worked out. However, it subsequently developed that all of the factors that were studied are merely individual links in a complex system of processes, and that methods of healing based on methods of treatment of these links are not sufficiently effective. Thus, for example, neither the removal of sympathetic ganglia in cases of hyper-

tonic disease, nor the removal of parts of the stomach in cases of ulcers, nor the removal of the thyroid gland in cases of hyperthyroidism, has produced a permanent cure of the illness. In our opinion, the cause of the illness in all these cases has been a general disturbance of the complex control and regulation functions of the organism. Treatment of one link of a complex system of processes has not resulted in restoration of the over-all regulatory processes nor in the disappearance of the illness. From the standpoint of the general theory of functioning of a system, the influence of some one factor on the pathological process cannot serve as a proof that precisely this factor is the cause of the illness, since it may be only one of the links in a system of processes.

Sometimes the method of treatment adopted, although it does produce temporary relief from the symptoms, does not retard the development of the pathological process as a whole. Thus, for example, when it was concluded that a lowered concentration of thyroid hormones was responsible for myxedema while a lowered concentration of insulin was responsible for sugar diabetes, the method of treating these illnesses involved injection of the substances into the blood of

the patient--a course of action which led to temporary relief of the symptoms of the illness and the suffering of the patient which, of course, is of great significance for the patient. In the opinion of Ashby /59/, however, this method treatment does not remove the pathological condition as a whole. The cause of the illness consists in a disturbance of the general processes of control.

Thus it becomes more and more clearly necessary to study illness from the viewpoint of the general theory of functioning of systems, and to recognize the importance of the general theory of control as well as to develop methods of investigation which will make it possible to approach the study of illness as a complex system of processes.

Here the work of I. P. Pavlov is of great significance. I. P. Pavlov regarded illness as a complex system of processes in which the displacements due to the action of the pathogenic agent itself and those due to the operation of protective compensating mechanisms are closely interwoven. Here a major role is ascribed to the nervous system.

Pavlov advanced the highly important view that the very same control systems and processes which

under normal conditions are of great adaptive or protective value may lie at the roots of an illness. These mechanisms are expressed hypertrophically under certain conditions and become the basis for development of an illness. For example, the physiological mechanisms which cause an increase in blood-pressure level during a period of danger are of great significance in the life of animals, since it is necessary during periods of danger to assure an abundant supply of blood to the muscles to support their intensified operation (in combat with the enemy or in flight). As has been noted by G. F. Lang /38/, however, these very mechanisms form the basis for the development of hypertonic illness.

The work of I. P. Pavlov /54/ and his students and disciples /5,15,16,47,28,48/, who showed that the development of systems of pathological conditioned reflexes may form the basis for the development of an illness, have been of great significance. This important adaptive physiological mechanism may also become the basis for the development of a pathological condition.

The rapid development of conditioned reflexes connected with danger to the life of the animal may be of great adaptive value. Under certain conditions,

however, these same mechanisms may become the basis for the development of a pathological state of the organism /28,15,16,47/. As a consequence of the very simplicity and ease of formation of these reflexes, they may become the cause of a permanent elevation of the blood pressure.

Mechanisms similar to these form the basis for development of certain diseases of the gastro-intestinal tract and other pathological states. These are also based on adaptive reactions which prevent poisoning of the organism when toxic substances are taken into the stomach (for example, vomiting reflex). The capacity for rapid development of appropriate stable conditioned reflexes is of definite value for the prevention of poisoning. However, even these conditioned reflex reactions may, under certain conditions, form a basis for the development of an illness.

Broad new prospects have been opened for pathological physiology as a result of the development of cybernetics. As noted by Ashby /59,60/, cybernetics creates a general theory of the operation of complex control systems and it provides new techniques for the investigation of complex systems. As a result, it becomes possible to pass directly from the study of

isolated links and symptoms of disease to the creation of an integrated picture of its pathogenesis and the detection of the real causes of its appearance. The solution of this problem will be found possible only when the scientific workers working in various branches of patho-physiology have mastered the basic techniques of cybernetics and learned to apply these methods creatively to their fields of investigation. It would be incorrect to assume that this problem can be solved only by physicists or mathematicians.

We have had an opportunity to consider the question of the role of cybernetics in the study of mental illnesses /15/. In the present work we shall devote attention only to certain general problems of the use of neurocybernetics in patho-physiological studies. We feel justified in making the assertion that the difficulties encountered in the study of a whole series of illnesses (hypertonia, stomach ulcers, etc.) stem from the fact that we know as yet very little concerning the complex regulatory mechanisms and the complex control processes which are at work in the normal organism.

States of the system in which a change in one of its processes (component A) results in a whole series

of displacements in other systems with the final result that an influence arises which intensifies component A, i.e., intensifies the process which gave rise to the reaction, appear to us to be of great significance in the development of pathological conditions. Closed systems with positive feedback arise. The functioning of such systems has by now been thoroughly studied.

In our specialized work /15/ we have attempted to point out ways to the investigation of such a system in the development of mental illnesses.

In certain cases, a deviation in the work of the mechanisms related to the formation of new systems of conditioned reflexes and to modification of the working algorithms of these systems may be of great significance in the development of pathological states.

The results of such a disturbance are particularly marked as a result of the fact that a slight disturbance of these systems results in the formation of an entire complex of constantly renewed pathological reflex systems--which may result in serious disturbances of the operation of the regulatory mechanisms. It appears that this type of disturbance comes into play both in study of the problem of disorders of internal organs and in study of the problems of mental illnesses

/15/. In this case it is probable that the mechanisms which provide for the development of reflex systems related to the protective functions of the organism are of greatest importance. Since these systems are among the most active their deviations in the direction of hypertrophy are most frequently observed.

Knowledge of the general principles on which the control systems function and the use of special methods which enable us to investigate them effectively would appear to be of great value in analysis of the above cases of the development of pathological processes. This circle of problems is in the province of cybernetics. In this manner cybernetics may have a certain role to play in the study of pathogenesis, as noted by Acting Member of the Academy of Medical Sciences I. V. Davydovskiy.

The possibility of simulating certain general principles in cybernetic machines may have great value in the study of pathological phenomena.

There are various points of view concerning the problem of simulation in cybernetics. One of them was formulated in an article published in Pravda on 29 May 1959 by Academician A. Dorodnitsin: "The possibilities of modern electronic computers are so great that they would be able to perform practically any 'intellectual'

operation of which man is capable if he only understood the logic of these operations."

Certain investigators advanced the thesis of the impossibility of simulating conditioned reflexes on the ground that it is impossible to reproduce in models the complex biochemical and biophysical processes which play an important part in the operation of nerve cells.

However, such objections are based on misconceptions. A model never completely reproduces all properties of the object being simulated. But this is not sufficient to deprive simulation of its value.

In speaking of the simulation of the conditioned reflex, we have in mind not full reproduction of the entire phenomenon in the electronic model, but only the reproduction of superficial analogies in the work of the model and the object. Superficially, the model and the object are described by similar operating algorithms (see Chapter IV). In this case we are not interested in the complex of biochemical and biophysical processes.

In passing to the next chapter we should note that such psychological and physiological terms as "idea", "study", "memory", "the development of a conditioned reflex," etc. are frequently used in contemporary cyber-

netic literature to characterize the operation of machines. In employing this already established terminology we have in mind only the community of certain isolated principles and not identity of the phenomena in the brain and in the machine. Nor can we speak of reduction of psychic processes to the processes which unfold in machines.

CHAPTER II

THE THEORY OF AUTOMATONS
(A Short Survey of Research)

In this Chapter we shall consider the work of certain scientists with whom the development of cybernetics has been closely associated. These are works on the general theory of automatons.

a) "The Nerve-Network Theory"

A method created in recent years by a group of American neurophysiologists and mathematicians (MacCulloch and Pitts /41/, S. K. Klini /30/, and others), which has recently been defined as the method of theoretical neurology or "The Nerve-Network Theory," is of great interest for study of the physiology of the brain.

In 1943 the American scientists U. S. MacCulloch and V. Pitts arrived at the conclusion that since nervous activity is subject to an "all or nothing" law, neuron

events and the relationships between them may be studied by the means of propositional logic. On the basis of certain assumptions, they created an abstract model of the neuron--the formal neuron (For a more detailed discussion of the formal neuron see Chapter VI).

Using a special mathematical apparatus for investigation of networks constructed of such neurons, they determined the classes of events which can be represented in such networks. However, the result of MacCulloch and Pitts is rather difficult to understand and this prompted Klini and later Medvedeva to question once again whether it is possible to represent events in nerve networks and finite automatons.

In considering this problem, Klini introduces the concept of the regular event: "An event is referred to as regular if there exists a regular set of tables which describe this event in the sense that the event occurs or does not occur depending on whether or not the entry is described by some table of this set."

It was found that we present the class of regular events and only this class in nerve network and finite automatons.

Formulating this conclusion somewhat differently, Klini shows that primitive-recursive events are pre-

sentable*.

Let us consider as an example an event which is not representable in such networks /30/.

The work of Yu. T. Medvedev /44/ sets out to obtain a result which is more easily reviewed than that of Klini.

He introduces the concept of the finite automaton: "An object with a finite number $n \geqslant 1$ of states a_1, a_2, a_m and a finite number $n \geqslant 1$ of inputs I_1, I_2, I_n is referred to as a finite automaton A. Each of the inputs I_k in itself determines a certain reflection $I_k a$ of the set m of states. Under the influence of an input I_k $(k = 1, 2 \ldots n)$, the automaton A passes from a state a_i $(i = 1, 2 \ldots m)$ to a state $a_j = I_k a_i$."

All finite automatons, including the nerve networks of MacCulloch and Pitts, come under this definition.

They go on to discuss certain events which they call "elementary" and basic operations performed on events.

Let us explain what is meant here by the word "event." Factors which are external to the automaton and give rise to disturbances of one or another input are called symbols. "Any combination C of symbol appearances may be referred to as an event E about the

*See reference 31 for primitive-recursive events.

symbols S_1, S_2, S_n. In other words, every event is defined by the resolution of a certain set of finite ordered symbol sequences" /44/.

As an example of an elementary event, let us consider the event E--an event which occurs when, and only when, there appear symbols with which the symbol Si appears at the present moment.

Six basic operations are performed on events. The conjunction E_1, E_2 may serve as an example of a basic operation, i.e., the event occurs when both of the events E_1 and E_2 occur.

The outcome of Medvedeva's work is the theorem:

"Those events which can be obtained from elementary events by way of a finite number of applications of the basic operations, and only those events, are representable".

Thus the events which can be represented in a finite automaton constitute a limited class of events. It does not follow from this, however, that non-representable events have any sort of biological significance.

The neuron model constructed by MacCulloch and Pitts is not unique. In a report before the International Conference on Information Processing held in Paris in 1959, D. Willis /22/ suggested a plastic-neuron model,

i.e., a neuron which changes its logical properties in accordance with its activity. Willis asserts that this form of the plastic-neuron model is compatible with the large capacity and the clearly defined arbitrary selection characteristics of the human memory.

The formal model of the neuron differs in many respects from the real neuron. Thus, the real neuron can transmit the intensity of stimulation by sending repeated impulses with variable frequency.

However, the analysis of nerve networks consisting of neurons closely similar to real neurons is highly complicated mathematically, since time parameters and the time-variable excitation threshold of the neuron appear in the description.

An interesting question is considered in the work of K. de Lieu, E. F. Moore, C. E. Shannon, and N. Shapiro entitled "Computability on Probability Machines". Is there anything that can be done by a machine with random elements, but cannot be done by a deterministic machine? It develops that a certain class of probability machines possesses somewhat higher capabilities than the deterministic machines.

In itself, the method used by MacCulloch and Pitts and by others cannot, of course, solve the prob-

lems encountered in study of the brain. Positive results can be achieved only by combined use of various methods of investigation; here the physiological method of investigating higher nervous activity, as worked out by I. P. Pavlov, will be of major significance. The nerve-network theory, however, is a valuable complement, which broadens the prospects for investigation considerably.

b) Synthesis of Automatons

Numerous investigators are interested in problems of the synthesis of automatons. Certain basic properties of the brain are taken into consideration in this synthesis.

In particular, J. T. Calbertson in his work, "Certain Non-Economic Researches" /29/ considers the question of the principles of a robot which might be constructed to possess capacities for complex forms of behavior without limiting his speculation in any way whatsoever in regard to the number of working elements used or the dimensions of the machine.

He considers two types of robot--a robot without memory and a complete robot.

The robot without memory is constructed as follows: He selects a certain number of receptors and a certain number of effectors and composes a program. A certain

combination of effectors is set up in correspondence in the program of each combination of receptors (See Chapter VI). Then the robot is assembled according to this program.

The complete robot differs from the robot without memory in that it has memory cells and the robot "remembers" everything that has happened to it. The program for the complete robot is approximately the same as for the robot without memory, only each combination of effectors is set up to correspond to a definite set of memory cells.

Calbertson comes to the conclusion that the complete robot can in principle carry out any specified program, "cleverly solve problems, compose symphonies ..." etc.

"Is it possible to construct a complete robot that behaves itself in the same way as John Jones?"...

Is this true? It does not seem so to us. Can such a robot compose a symphony or perform any creative work at all?

It is hardly likely that it could do this; its creator would have to do all this for it in advance in composing the program.

Since the connections between the effectors

and the memory cells are fully determined by the program, its "memory" can do nothing for this robot. It is unable to accumulate experience and behave in accordance with its accumulated experience. Such a robot can be created only for a definite state of the environment and will expire if the environment changes. Furthermore, its potentialities are no different from those of the robot without memory. Indeed, suppose we set up every set of memory cells in correspondence with a definite set of receptor neurons. Let us leave the program and the effector neurons just as they are in the complete robot. In this manner, we shall obtain the robot without memory with only the number of receptors decreased.

It is clear from this that the construction of robots of the type described by Calbertson makes no sense. It is necessary that the robot be able to accumulate information from the external medium and to act on the basis of its accumulated experience. To accomplish this the connections between the effectors and the memory cells must not be predetermined; they must be established as a result of interaction with the environment. The conditional-probability machine of Attlee, the "Perceptron" of Rosenblatt, and the automaton described at the end of this book may be in-

cluded among such automatons.

These three works are similar as regards their final purposes, but the routes taken are different in all three cases.

Attlee's machine /7,8/ is based on two familiar mathematical relationships: The first is the inclusion relationship of set theory and the second is the conditional-probability relationship. The machine classifies external disturbances on the basis of the first relationship and certain concepts are formed in the machine. Certain concepts may occur in conjunction with a certain degree of probability, i.e., there exists a certain conditional probability between the appearances of these concepts. Establishment of the value of this conditional probability results in a conditioned reflex if the machine is equipped with effector mechanisms.

If in addition to the direct paths between the input signals and the conditional probability machine there are paths with delays, then the machine will be able to distinguish time representations.

An article published in the magazine "Aviation Week" /18/ concerning the creation of the "Perceptron" electronic computer by the American Ozone Block is also of interest. It is stated in the report that this machine is capable of

classifying, sensing and representing symbolically its external environment and also of taking into account completely new and unforeseen changes in its environmental condition.

Although it is difficult on the basis of the short report to appreciate the principles on which this machine is constructed, certain details of its operation are similar to the classification machine of Attlee. Specifically, the associating cells of the "Perceptron" (memory cells) are connected randomly, i.e., it can be stated with a certain probability that a given cell is connected to another. The same state of affairs is observed in Attlee's machine. Like Attlee's machine, the "Perceptron" is capable of learning.

An automaton that is also capable of learning and identifying time representations is described in the last chapter of this book. The principles on which it is based differ somewhat from the principles of Attlee's and Rosenblatt's machines.

An interesting report from Ashby /61/ considers the problem of creating a thought-capacity amplifier. Ashby indicates that thought capacities can be reduced to the suitable selection of the required variant from among a set of variants. It develops that a machine which is capable of selection can be created, but the time of selection is

extremely long. Ashby indicates methods of reducing the time required for trial.

The thought-capacity amplifier is based on the homeostat.

The problem of concept formation in automatons has attracted great interest. A report by Mackay entitled "The Problem of Concept Formation by Automatons" /42/ is devoted to this problem.

Mackay indicates two directions in which the solution may be sought. He considers it possible to construct an automaton that forms abstract concepts. Such an automaton must continuously work out tentative organizing programs, which are compared with signals from the environment. For an abstract concept to be formed it is necessary to have a hierarchy of such systems with each system forming a concept of a higher order of abstraction.

The report entitled "Experiments on a Machine that Thinks and Learns" by the English scientists T. Kilburn, R.Z. Grimsdale and F.H. Sumner, who carried out their experiments on a general-purpose digital computer is of interest in this sense. A criterion for evaluating the usefulness of the programs was introduced and the machine selected useful programs.

Although at the present time all programming work

is done by humans, it is possible that we shall succeed in using machines for the composition of programs as well.

The reports of E.F. Moore /46/ consider methods of investigation by means of which the experimenter, without knowing the internal structure of the automaton, can form concepts concerning the principles of its operation, draw conclusions as to the identity or nonidentity of different automatons and their internal state at a given moment of time. These methods of investigation are based on a rigorously formalized system of operations which the experimenter performs on the automaton in the course of the experiment and on special methods of analyzing the systems of responses with which the automaton responds to these operations. The discussion presented is of interest for study of the operation of the brain, which is also based on the performance of series of specially designed operations.

J. Neumann's system of ideas on ways to synthesize reliable automatons from unreliable "components" (elements) /51/ is also of great interest. An essential difference has been detected on comparison of the brain's operation with the operation of cybernetic machines; this consists in the fact that in the machines, the failure of a single element (for example, a radio tube) results in disturbance of the operation of the entire system.

In the nervous system, however, the removal or destruction of even a large number of nerve cells does not usually result in an irreversible disturbance in the work of the brain. On the basis of these facts, J. Neumann /51/ arrived at the conclusion that there exists in the brain a special system of nerve-network organization which possesses the singular important property of stability to disturbance, by virtue of which the cutting out of a single element does not result in a disturbance of the over-all system's operation. Each nerve cell is an "unreliable" element, i.e., an element which may cease to function. But the nerve network as a whole operates as a completely "reliable" system.

J. Neumann attempted to explain the organizational and operational principles of the systems which could form the basis of this effect, and to develop a theory to enable us to build fully reliable machines from unreliable elements. Such machines would not stop working when individual elements are switched off. On the basis of the investigation which he conducted, he created a system of concepts which considers the theory of this problem. He worked out a schematic diagram of a machine which, although it was composed of "unreliable" elements, would work as a fully reliable system, i.e., would possess properties characteristic of the brain.

Such are the basic directions of work in cybernetics at the present time. Other research is devoted to the synthesis of automatons that simulate the functions of the brain.

However, the physiological methods alone are likewise incapable of solving these problems.

Therefore scientists in the various specialties--mathematicians and physiologists, neurophysiologists and engineers--must work together in order to arrive at a successful solution of the problems that arise in study of the brain.

CHAPTER III

CONTROL SYSTEMS OPERATING FROM FIXED PROGRAMS

Let us begin our exposition and analysis of the operating principles of systems which are capable of highly complex types of purposive behavior on the basis of a previously specified program. Such systems are not capable of independent development of new forms of behavior (of the learning process).

To a certain degree, the behavior of the spider which constructs a complex configuration of filaments in the form of a cobweb and the complex behavior of ants or

bees might be taken as examples of the operation of systems of this type. The behavior of the dung beetle which constructs a special cocoon in which its larvae will develop might also be noted as an example. This behavior recognizes, as it were, the needs which will be felt in the future after the birth of the new individuals and provides conditions for the satisfaction of these needs.

The development of conditioned reflexes is also possible in insects.

The machines which control the operation of industrial undertakings and provide for the manufacture of products also show complex forms of behavior.

In the former case, the sequence of operations carried out by the insects (their work program) is determined by hereditary forms of organization of its nervous system which were developed in the process of evolution. In the operation of the machine, the work program is provided by the automatic-equipment designer. The behavior of the system may be highly complex in either case. For example, the construction of a cobweb or an ant hill must provide the possibility of sequential transition from the performance of one operation related to one form of activity to another. The system can pass to a later stage of the work only after completion of the preceding phase.

The nature of the insects' motions must be determined in a complex manner by the results of the previous activities and the stage to which the work (for example, the construction of the ant hill) has been carried. The behavior of the insects depends in each of its stages on a whole intricate complex of stimuli arising from the environment.

It is important to note that in carrying out complex forms of behavior, it is found possible to vary the program of activity of the animal in accordance with the results of its previous activities and to switch from one program of activity to another.

In this connection, the experiments conducted by the famous Polish scientist Ya.K. Dembovskiy /27/ are of great interest. It was shown, for example, that the removal of a diving beetle's swimming legs results immediately in a shift to another system of activities which permits the insect to move by another method.

The possibility of switching behavior from one program to another accounts for the surprising results achieved by insects, e.g., in the construction of an ant hill or cobweb under conditions in which temperature, wind direction, humidity, the quality of the structural materials (in the case of ant hill construction) and other factors are continually changing. Yet in each case the shape of the

cobweb is found to be precisely adapted to the contours of its location, and in cases where the integrity of the cobweb or ant hill has been disturbed the activities carried out by the insects are in strict correspondence to the nature of the damage that has occurred.

The complex forms of behavior described here are basically instinctive in nature. Although variants which permit transition under certain conditions from one program to another may be provided in the actual structure of the behavior, all of these variants are rigorously predetermined and their number is limited.

The introduction into the operation of the system during the course of the experiment of any disturbances which could not take place under the natural living conditions of the animal and consequently could not be provided for in the process of evolutionary development by means of an appropriate program results in destruction of the entire cycle of behavior. This is attested to by the numerous and well-known experiments in which bees have continued to seal honeycomb cells even though the honey has been removed from them.

The work of the endocrine glands is also of great importance in the execution of complex forms of behavior. It has been demonstrated for example that the complex forms

of behavior related to reproduction are closely associated with the presence of the sex-gland hormone in the blood.

It should be noted that the design of machines which control the operation of industrial undertakings also usually provides the possibility of changing the programs and switching the operation of the system from one program to another in accordance with the results of the preceding activity and the sum of the external influences.

a) The Reflex Principle in the Operation of Control Systems

A characteristic property of systems of this type consists in the fact that they work on a general principle which might be referred to as the principle of the "reflex reaction".

The essence of this principle consists in the fact that the behavior of the system is a series of responses to definite signals received from the environment. The general scheme of operation of a system of this type may be characterized as follows. A certain signal acts on the system and in response to this signal the system passes to a state K_1 and performs the activity c_1. As a result of this action, certain changes appear in the environment. Information concerning these changes enters the system in the form of a signal K_2. The signal K_2 causes a change in the state of

the system from K_1 to K_2 and the appearance of a new motion b_2 which in turn gives rise to the appearance of the information a_3 and so forth.

Behavior of this type on the part of the control system is determined by the fact that its operation proceed in close interaction with the external medium surrounding the system, or (using the terminology of Mackay /42/), "the adaptive field of activity of the system". Here the behavior of the system, which is directed toward a change in the external medium in the appropriate direction, must be continuously corrected by the input and processing of information reflecting the results of the system's operation in the various stages. In this manner a complex process of interaction between two systems -- the brain and the external medium -- takes place in the course of complex behavior.

In the case of the machine's operation, a complex system of interaction comes into play between the control system and the controlled object. This problem is analyzed in detail in the specialized work of I.I. Gal'perin /25/. The problem of the principles of operation of automatons is also illuminated in the works of S.K. Klini /30/, J.T. Calbertson /29/, B.M. Mackay /42/ and other authors.

The principle of the reflex reaction was first introduced to science by Descartes to account for the beha-

vior of animals. Here Descartes made use of the analogy between the operation of living organisms and the principles of the water clock, waterworks and other mechanical devices which came into being during the 17th century.

Scientific study of the complex forms of behavior of animals became possible on the basis of the mathematical teachings of I.M. Sechenov /56/ and I.P. Pavlov /54/.

According to the basic points of this doctrine, the activity of the brain is completely determined by conditions in the environment. The work of the brain is a system of reflex responses to extremely complex sets of stimuli arriving from the external medium. Here a distinction is drawn between several types of reflex activity:

a) the conditioned-reflex activity which forms in man and animal during their lives and which is based on the development of systems of conditioned reflexes (the learning process) and

b) unconditioned-reflex activity which arises in the animal at the moment of its birth.

The instinctive conditioned-reflex form of behavior is a property of man and animals at different evolutionary levels. In the lower animal, however (and in insects in particular), these forms of nervous-system activity have been extensively developed and are essentially what determines the behavior of the animals.

Regulation of the activity of the internal organs is also accomplished on the principle of complex systems of unconditioned reflexes. When certain stimuli act on the organism, we observe a highly complex pattern of redistributio in the unfolding of the various processes in the organism. When a painful stimulus is applied, for example, the blood-pressure level, the coagulability of the blood, and its sugar content all increase, the activity of the digestive gland is inhibited, and so forth.

The operation of mechanisms which maintain constancy in certain functions which are of vital importance for the organism under changing conditions (constancy of the concentration of sugar in the blood, constancy of the blood pressure level, etc.) is of great importance.

In study of these complex processes, researchers encounter situations in which a certain reaction of the organism depends on an entire ensemble of interoreceptive and exteroceptive signals and constitutes an integrated response to this complex of stimuli.

A whole series of pressing problems arises in study of the laws on which the functioning of systems of this type is based in the plan of theoretical cybernetics. We encounter the problem of study of mechanisms which are capable of providing for complex forms of behavior of the

system. The problem of the principles which make it possible to switch the system from one program to another is of great importance; the same applies to the problem of the operation of systems which are capable of reacting to complex sets of signals.

The work of Calbertson /29/ which is analyzed in Chapter 2 is of interest in consideration of these problems. Even though the activity of the complete robot may be highly complex, it is still fully determined by a system of "unconditioned reflexes" (the program).

We stress once more that the development of new programs is impossible for a system organized in this way.

CHAPTER IV

SYSTEMS CAPABLE OF INDEPENDENT DEVELOPMENT OF NEW PROGRAMS FOR THEIR OPERATION

One of the most important problems of cybernetics is the problem of study of the so-called "self-organized" control systems, which are capable of independently working out new programs for their operation. Only the basic purposes of its activity need to be fed to such a system. It should possess the capacity to find the optimal method of

solution of a new problem placed before it by itself in the process of its operation. Here, the "method of solution" may be an extremely complex sequence of operations (commands) which are carried out in response to the appearance of certain external signals (the complex program of operation). The concept of "the purpose of the operation" may, however, include supplementary conditions related to the necessity of avoiding certain states and situations which might result in breakdown. The machine may find it necessary in the process of working out the program of its activity to set up new intermediate goals. As a whole, the process is extremely complex.

Analysis of the principles of operation of the brain is of decisive significance in study of this problem.

One of the basic properties of the brain's operation is its capacity for designing new forms of behavior.

When a new situation arises for an animal, new forms of behavior also appear to fulfill its needs.

A scientific analysis of these properties of the brain was given in the works of I.P. Pavlov /54/ and his students /2,4,19,21,37/. A theory was created to account for certain complex forms of operation of the brain. The basic proposition of this theory is that the formation of complex conditioned-reflex systems forms the basis of the

new complex forms of behavior which arise in the life processes of animals.

A method which involves placing the animal in a special chamber was used to study this phenomenon. Here the basic idea was that the animal would be isolated from its natural environment and it would be possible at the same time to apply different disturbances to it in the form of various signal complexes.

This method made it possible to reveal the basic relationships which characterize the development of new forms of behavior (new systems of conditioned reflexes).

The basic points of the doctrine created by I.P. Pavlov and his school concerning the operation of the cerebral hemispheres are widely recognized /54,2,5,19,20,21,37/. In view of this we shall not dwell in great detail on this problem.

The investigations carried out in this direction by P.K. Anokhin resulted in the creation of the concepts of the "activity acceptor" and "return afferentation" /2,3,5/.

According to these concepts, the simple scheme of the reflex arc should be supplemented by an important component. This component is rendered necessary by the fact that after executing a conditioned-reflex reaction, the animal must obtain information concerning the result of

this activity. This information must then be compared with some criterion which has been created earlier in the brain and which would permit evaluation of the success or failure of the activity which has been carried out. The animal shou[ld] either repeat this activity (in case of a negative evaluation) or pass on to some new activity in accordance with the results of the evaluation.

The ideas of P.K. Anokhin supplement the concept of the mechanism of the closed reflex arc which was created before his time; this provides for consideration of a reflex system as a unified complex in which the realization of one link of the conditioned reflex provides a requisite for the transition to the next link.

The doctrine of I.P. Pavlov /54/ concerning the systematic nature of the operation of the cerebral hemispheres is of great significance in the study of this problem. It eliminates the one-sidedness of gestalt psychology and behaviorism and creates a basis for materialistic study of the complex forms of the brain's operation.

Interesting research in this direction has been carried out in the laboratories of P.S. Kupalov, L.G. Voronin, and S.N. Braynes.

Researches carried out by L.G. Voronin /21/, P.S. Kupalov /37/, S.N. Braynes /14,12/, N.A. Rokotov /55/, A.V.

Napalkov /49,14/, K.A. Iordanis /14/, I.A. Alekseyeva /1/, and others have been devoted to the laws of development of complex systems of conditioned reflexes in various species of animals and also the complex phenomena and relationships which appear on study of conditioned reflex systems.

Recently, certain scientists have proposed a sharper demarcation between the concept of the "classical salivary conditioned reflex" of I.P. Pavlov and the concept of complex systems of motor reflexes as a more complex phenomenon in the behavior of animals.

In our opinion, there is no basis for such a demarcation, since I.P. Pavlov applied the term "conditioned reflex" in a broad sense. He repeatedly stressed the complex "systemic" character of the activity of the cerebral hemispheres.

Together with this we feel obliged to stress that the contemporary development of science and in particular the development of the theory of self-organized control systems poses a number of new problems and in many cases requires both broad-scale theoretical consideration of the problem and the development of new methods of investigation.

Study of the laws covering the development of a system of conditioned reflexes under experimental conditions frequently does not solve the problem of the possi-

bility and directions of formation of this system under the conditions of the life of the animal in nature. In the course of developing a circuit of reflexes, the experimenter does not* apply a whole series of artificial disturbances: he cuts in various signals at certain moments of time and in a certain order, he induces a given motion at a moment suitable to him and so forth. These stimuli may be absent under the actual living conditions of the animal.

The study of the laws of formation of complex reflex systems has taken shape in a definite scientific direction having specific techniques and problems of investigation. From the viewpoint of the problems of this direction of science, the use of methods of investigation which facilitate the development of reflex systems is necessary and fully justified.

However in working out the broader theoretical problem of study of the operation of self-organized control systems it becomes necessary to take rigorous account of every operation performed by the experimenter in the course of the experiment. It also becomes necessary to consider the influence of motions of the animal on the external medium and the presence in the external medium of a certain system of relationships between the phenomena which determine the appearance of new signals. On the whole we en-

*Translator's note: Thus in text.

countered a new problem of study of the complex pattern of interaction between two interrelated and interacting systems — the environment and the organism. This problem is no longer inherently part of the field of physiology and is one of the most important components of neurocybernetics. Moreover, the solution of this problem is of essential value for study of the brain's operation. This problem is closely associated with the study of other problems of cybernetics, specifically, with the study of the laws governing the processing of external information in the process of formation of new conditioned-reflex systems, with the problem of detecting the corresponding algorithms, with the problem of selecting "useful" information from the over-all flux of information entering the brain and with a series of other problems.

a) Interaction of Two Systems (Brain and Environment)

The formation of a new conditioned-reflex chain is accomplished as a result of processing of the information which arrives from the external medium in the form of complex sets of stimuli which act on the sense organs. However, the input of information into the brain is also dependent on the motor reactions which the animal performs in the process of forming the reflex chain.

Any motion directed toward a change in the environ-

ment results in the input into the brain of a new flux of information.

In a number of cases, the acquisition of certain important information is altogether impossible without the organism's asserting some sort of action on the external medium surrounding it. For example, it is well known that a flame may be obtained by striking a match on its match box. However, information concerning the possibility of obtaining fire may be obtained only when the man has made the active motion related to igniting the match.

It must be emphasized that if animals were to perform all the motions which they are capable of performing by virtue of their physical organization and if they remembered all the information which then arrived from the external environment, then the formation of a new purposive behavior form would obviously be impossible because the brain would be overloaded with a tremendous quantity of unnecessary information.

The most important singularity of the brain's operation is its capacity for selecting, sensing and storage of only that information which is necessary to satisfy certain requirements.

Another important singularity of the brain is the fact that in the formation of new behavior patterns, the

animals do not perform all the possible motions, but carry out their motor reactions in a certain optimal sequence (according to definite rules) with the result that they obtain the maximum quantity of "useful" information with a minimum number of trial motions.

Here the nature of the new trial motions which are carried out depends in a complex manner on the nature of the information arriving at the brain as a result of the previous motions.

The complex pattern of interaction between the environment and the brain arises in this manner.

In speaking of the external medium surrounding the animal, we wish to introduce a certain refinement. Usually, the brain enters into interaction not with the entire "external medium" but only with a certain part of it. As a result, it is more convenient to speak not of the external medium but of a certain "field of activity" /42/, thereby limiting the field of activity of the brain.

A similar system of interrelationships is observed in the operation of the machines that control the operation of industrial undertakings. In this case the control process presupposes the existence of interaction between two interrelated systems -- the controlling system and the object controlled by it (the field of activity of the system).

The process of control consists in the application of a certain influence by the controlling system on the controlled object with the result that various types of changes occur. It is the information concerning these changes which is fed into the control system that forms the basis on which a self-organized control system can develop a new optimum mode for its activity.

In view of this, it seems convenient to us to consider the problem in its general form on the level of study of the interaction of two systems, one of which (the brain or the control system) processes information arriving from outside in the course of its activity and composes a program for its operation (a system of conditioned reflexes) on the basis of this information. The other system may be referred to as the controlled system or, to use other terminology, may be termed the "adaptive field of activity" of the control system (external medium).

Let us suppose that some control system is capable of performing operations $b_1, b_2, b_3, b_4 \ldots b_n$ and senses stimuli (information) which arrive from the object of control in the form of signals $a_1, a_2, a_3 \ldots a_m$.

The control system (the brain) must perform a certain task in the course of its activity. In its general form this task may be expressed as follows: the system must

use a certain sequence of operations to obtain a certain necessary state of the controlled object (the external medium) "k".

Let us suppose that the external medium contains a certain possibility of attaining "k" by means of a definite system of operations. This possibility may be expressed, for example, by the following scheme: $a_{11}-b_4-a_8-b_{13}-a_3-b_6-a_{37}-b_1-k$.

This signifies that for the state "k" to arise in the environment (controlled system) it is necessary to carry out a whole series of successive operations:

$$b_4-b_{18}-b_6 \text{ etc.}$$

Here, each of these operations must be performed in response to the appearance of a certain stimulus

$$a_{11}\ a_8\ a_3 \text{ etc.}$$

This possibility is itself determined by the system of laws which exists in the environment, as well as by the character of the operations which the animal is capable of performing.

We consider it important to stress that this possibility exists objectively and that the process of developing a new program of operation may be reduced to the identification of this system of laws.

The development of a new program of operation is

accomplished under these conditions as a result of operation of the control system on the external environment (the object of control) and processing of the information that arises as a result. In the simplest case the control system will perform, one after the other, all possible operations (complete survey). Let us analyze the possible results of employing this principle of activity: let us assume that the control system begins to perform in sequence all of the possible operations b_1, b_2, b_3, b_4 or b_5, b_6, etc.

As a result of these operations certain changes occur in the object of control (the external medium). Information concerning these changes enters the control system in the form of the signals a_1, a_2, a_3 or complexes of signals, for example $a_3, a_4, a_5, a_8, a_6, a_3$.

A new program of operation which leads to the attainment of the goal "k" (food and water) should arise on the basis of the results of processing this information. In analyzing this process it must be remembered that in addition to the individual reactions the system will have to experience variants of the various reflex chains, e.g., $a_3 - b_4 - a_6 - b_8$ or $a_5 - b_7 - a_6 - b_4$ and so forth.

In this case judgement of the correctness of one or another chain will become possible only when the phenomenon "k" appears in the environment (attainment of the

goal), i.e., only when the control system (brain) accidentally performs the correct sequence of activities $a_{11}, b_4, a_8, b_{18}, a_3, b_6, a_{37}, b_1$—k after a long period of testing the various possible behavior variants. The theoretically possible number of variants which the control system must test before it accidentally stumbles on the proper variant can be calculated. The problem consists in the choice of the sole correct variant from among an extremely large number of possible variants. Such a problem has been analyzed in a special report by Ashby /61/. He arrived at the conclusion that a complete survey of all possible variants would require an astronomical outlay of time and would prove impossible in practice. A special model of the homeostat that adjusts itself by way of a complete survey of variants has been created for study of this problem.

A report by Ashby /61/ indicates certain directions which may result in shortening of the time for selection of the necessary variant. One of the important factors which provides for a shortening of the selection time is the operation of certain qualitative relationships in the surrounding external medium. As a consequence of these relationships, not just any of the stimuli (a_1, a_2, a_3), but only strictly determined signals may arise in response to the performance of some action a_1. This reduces the

time spent in surveying the variants. We must ascribe significance to the fact that as a result of the existence of systems of external relationships, and as a result of the existence of the continual processes of motion and transformation which characterize the external objective world, different signals, including the a_4, a_8, a_6, etc., which enter the reflex chain, will appear with a certain probability at all times in the medium surrounding the man or the animal.

The probability of the appearance of these signals depends on the degree of organization of the external medium, on the ability of the animal to perform various motions, and on other factors. The appearance of various signals in the external medium may be of great significance. Special techniques employed by the animal may be used on the basis of this phenomenon to achieve a sharp reduction of the number of trials made.

In this manner, we arrive at the conclusion which has importance for us--namely that not only the study of the brain, but also examination of the basic forms of interaction of the organism with its environment is of decisive importance for consideration of the problem of self-organized control systems.

According to the basic tenets of dialectical

materialism, highly complex systems of cause and effect relationships among the various elements of the external medium have an objective existence in it. This doctrine proves important in study of the system of interrelationships which arises between an organism and its environment in the process of developing new conditioned-reflex chains. As a consequence of the existence of a complex system of interrelationships in the environment, the motions performed by animals may give rise to a whole chain of reciprocally-related processes; the result is the input of a large quantity of heterogeneous new information into the brain.

The higher the degree of "organization" of the environment, and the greater the extent to which cause-and-effect relationships prevail in the environment, the greater will be the quantity of information obtained by the animal in response to the motion that it performs.

It must also be taken into account that the environment is in a state of continuous change and motion. This point is important, since the conclusion that an animal can obtain certain information pertaining to the interrelationships prevailing in the environment even without performing some active motion proceeds from it. The discussion presented suggests the possibility of

reducing the number of trials. It is important to stress, however, that a reduction in the number of trials cannot be attained automatically; for this purpose it will be found necessary to use special "procedures" which are related both to a definite sequence of motions performed by the animal and to the use of certain principles in selecting the information arriving from outside. The question arises as to a certain definite rational organization in the sequence and character of the disturbances (trials) which the self-organizing system applies to the controlled object during the period of "self-education".

The question as to the criteria for evaluating the usefulness of the various motor reactions acquires a great significance.

Together with this we encounter the problem of creating a certain evaluation system for selection and fixation in the memory of only that information in the stream of information arriving from the controlled object which may prove useful in the attainment of the goal "K" which has been assigned to the system in advance.

The appearance, in the course of the "self-teaching" process, of intermediate guide points which would permit the evaluation of the usefulness of the

various motions and the importance of the various information coming into the brain would evidently be of great significance for the solution of this problem.

Thus the problem arises of seeking out a certain sequence in the control system's operations which would permit its rapid and accurate development of new operating programs (new reflex chains) without making an exhaustive survey of all the variants. These operations must obviously include both definite rules for the application of disturbances to the controlled object and definite rules for the evaluation and processing of the information arriving from outside. Here, of course, each successive action must be determined in a complex manner by the results of the preceding actions.

As was correctly noted by A. A. Lyapunov /40/, here we speak of the problem of finding the algorithms of operation of self-organized control systems. Here we encounter the problem of study of "higher-category" algorithms, algorithms on the basis of which new operating programs (reflex chains) may be worked out; in other words, algorithms which make it possible for the control system itself to find the new and different information-processing algorithms which are necessary under the new conditions of operation of the cybernetic system.

This problem is also of vital importance for cases in which the control system which already has a definite program must take its "mistakes" into account and find ways to eliminate them.

The brain possesses such algorithms. They arose in the process of evolution as a result of natural selection.

In studying the algorithms of the brain's operation, it is important to remember that it is frequently necessary for a control system to work out not only operating programs in the form of sequences of different actions but also much more complex programs. For example, it may occur in the operation of a chemical enterprise that the presence of some substance retards an entire system of chemical reactions. A self-organized control system should be able to detect this substance and then find ways to eliminate it.

Cases in which two independent components are necessary to accomplish a certain stage of the process may be taken as a second general case of control-system operation. For example, the simultaneous presence of two substances (A and B) may be found necessary in a certain stage of a process in the operation of a chemical enterprise. The self-organized control systems

should have the capacity to: a) determine just which substances are necessary, b) work out a method of acquiring the substance A, c) then develop a method for acquiring the substance B; d) only then will it be able to effect full development of the optimum regime of operation of the enterprise.

In speaking of these more complex cases of control-system operation, it must be noted that physiologists also encounter similar forms of operating-program development in study of the work of the brain and that the study of these forms of operation raises the question of seeking out more complex information-processing algorithms in the brain.

The above form of examination is unusual for physiologists. Objections are frequently raised against the use of the term algorithm, which had not previously been used in study of the problems of development of conditioned-reflex chains.

In this connection, the authors feel it important to stress that the problems and methods of investigation of neurocybernetics do not coincide with the problems and methods of study of higher nervous activity. As a result, it is found necessary and helpful to use concepts and terms that have been adopted in this branch of

science.

b) Systematic Procedures for Study of the Brain's Information-Processing Algorithms

It is found necessary for study of the problems formulated above to develop certain special procedures of investigation which will permit an approach to study of the complex interaction between different systems. These systematic procedures should provide not only for scientific analysis of the work of the brain but also for analysis of the variations in the environment. It is therefore found necessary to reproduce the interaction of two systems in the course of the experiment. Any of several systematic procedures may be used in carrying out these investigations. In one of the variants, the experimentor may take the part of the external medium, by noting on paper prior to the experiment a definite system of "external regularities". Later, during the experiment, he must apply various signals in accordance with this scheme and the motions of the animal. Here he may also provide the possibility of random (independent of the motions of the animal) appearance of various external signals and establish a definite probability of their appearance. For example, the experimenter may apply various signals five times during each minute, in addition to observing the other rules. Apart from the experi-

menter, an automatic device whose operating program governs the appearance of the necessary relationships may also be used during the experiments. Certain algorithms of the brain's operations may be detected in this first stage of investigation.

The second stage of investigation is concerned with further analysis of these algorithms. It presupposes the creation of an automatic device in which the algorithms detected in the experiments on the animals should be realized. The final purpose of study of the operation of the automatic device should be to determine whether these algorithms can actually provide for the development of new programs of operation for the system. In this case, if the automaton were to prove capable of independent formation of new programs for its work, this would be an indication that the conclusions drawn were correct. In the contrary case, study of the operation of the automatic device would permit us to determine what constitutes the inadequacies of our concepts concerning the algorithms of the brain's operation and enable us to mark out the course of new experiments on the animals. In our opinion, therefore, the process of investigating this problem must include several phases, some of which would be carried out on animals and others by way of in-

vestigating the work of the automatic device.

Study of the operation of the cybernetic machine may provide answers to a number of important questions relating to the determination of the conditions in which a given algorithm can provide for the formation of new operating programs, and environmental conditions under which it is ineffective.

Experiments in which studies were made of the interaction between two radio-electronic systems, one of which would embody certain algorithms of the brain's operation while the other served as a model of the environment and reflected its basic properties, might also be of great interest.

In our research, we used a special chamber to conduct the physiological part of the experiment. The operating principle of the chamber made it possible to apply a large number of different types of stimuli--bells, metronome sounds, etc.--and to register a large number of different motions of the animals--jumping onto a pedestal, pressing a pedal with a paw, etc.

The experimental technique made it possible for the experimenter to apply the various sets of stimuli at will, and to record all motions of the animals. It also enabled him to create different systems of relationships

(systems of interrelationships among the various stimuli) of varying complexity in the experimental environment about the animal. For example, an experimenter wrote down the definite scheme:

$$\text{bell} \longrightarrow \begin{matrix}\text{leap to}\\\text{pedestal}\end{matrix} \longrightarrow \text{whistle} \longrightarrow \begin{matrix}\text{pressure}\\\text{on pedal}\end{matrix} \longrightarrow \text{food}$$

This scheme represented a definite system of relationships which were artificially created in the animal's environment during the course of the experiment. Here, the experimenter himself played the role of the environment. In accordance with the movements of the animal, he used this scheme as a guide in applying various stimuli. If, for example, the animal jumped up onto a pedestal when a bell was rung, the experimenter blew a whistle. It is convenient to use a system of letter symbols to characterize these relationships. For example, the system of reflexes given above may be represented nicely in the form of the scheme

$$a_1 — b_1 — a_2 — b_2 — \text{food}.$$

Systems of relationships in which the acquisition of food was possible only in the simultaneous presence of two signals, e.g., P and R, could also be created. We present the scheme

$$\left.\begin{matrix} a_1 — b_1 — a_2 — b_2 — P \\ a_3 — b_3 — a_4 — b_4 — R \end{matrix}\right\} b_5 — a_6 — b_6 — \text{food}$$

It will be seen that with this system, in order for the stimulus a_6 to arise after the movement b_5, it was necessary that two mutually-independent signals R and P be present; on the other hand, there existed a system of relationships that could provide for the appearance of the signals R and P ($a_1 - b_1 - a_2 - b_2 -$ P and $a_3 - b_3$ $a_4 - b_4 -$ R).

Aside from the systems of rigid relationships, it was also possible to provide for the random appearance of the various signals ($a_1 - a_2 - a_3$ etc.) in the course of the experiment; here the probability of the appearance of the various signals could be fixed by the experimenter at the beginning of the experiment. In the course of our experiments, we provided for the animals an artificial environment that was under the control of the experimenter.

This external medium could be modified and reconstructed at the experimenter's will.

On subjecting hungry animals to these conditions, we observed that as a result of performing a certain sequence of movements and using certain forms for processing external information, the animal would, after a certain period of time, "divine" an objectively-created and "unfamiliar" system of external relationships that enabled him to acquire food. A new conditioned-reflex system (a

new program of operation) was worked out on this basis to make it possible to obtain the nourishment in the shortest possible time.

In conducting these experiments, the experimenter knew exactly both the nature of the external relationships and the nature of the new system of conditioned reflexes that emerged. He could follow the appearance of the various external stimuli. By using various forms of the experiment which involved the creation of different conditions in the external medium, the experimenter was thus enabled to study the system of rules in accordance with which the movements of the animal were carried out, and also to cast light on the procedures used by the animal to process information arriving from without. In this manner, it becomes possible to study the algorithms used by the brain in developing new forms of behavior (the new operating programs of the brain) in a new situation.

The second stage of the investigation was the creation of a cybernetic radioelectronic system (a learning automaton); see Chapter VI of the present work. The basic algorithms discovered in the animal experiments and underlying the formation of the conditioned-reflex chain were embodied in this machine. In the construction of the automatic device, we made it our goal to determine whether

these algorithms can actually provide for the operation of a self-organized system and to study the process of development of new conditioned-reflex circuits under various conditions and the number of trials necessary. New physiological experiments were then set up on the basis of the results of this study.

c) Information-Processing Relationships Underlying the Formation of a Simple Reflex Chain

A number of various algorithms were discerned; each of these was optimal under certain conditions and inapplicable under other conditions. These algorithms were quite complex, and for now we shall present only a few of the simplest instances.

Let us consider the algorithms which come to light in the development of a simple chain of reflexes (algorithm No. 1)

$$a_1 - b_1 - a_2 - b_2 - b_3 - a_4 - b_4 - \text{food};$$

where

$a_1, a_2 \ldots a_n$ are stimuli;

$b_1, b_2 \ldots b_m$ are various movements.

1. The animal performs various random motions ($b_1, b_2, \ldots b_m$) and senses the information that develops as a result ($a_1, a_2, \ldots a_n$).

2. If it obtains food several times after some

one of the movements (b_4) (if this movement coincides in time on several occasions with the acquisition of food), then a) the number of random movements diminishes sharply; b) the animal begins to perform the movement b_4 very frequently.

3. If the movement b_4 invariably coincides with the acquisition of food, no further changes are observed.

4. If the movement b_4 does not result in the acqusition of food or does not always do so, the animal begins to sense external information (a_1, a_2 ... a_n). If some stimulus (a_4) coincides with the motion b_4 and the acquisition of food several times, then a) the movement b_4 begins to occur only in response to the signal a_4; b) the animal stops receiving external stimuli.

5. In cases where the signal a_4 appears frequently and coincides with food, no further changes are observed.

6. In case a_4 (the conditioning stimulus) has not appeared for a long period of time or is not reinforced, the random movements reappear and the information which arises as a result of these movements begins to be sensed.

7. If one of the random movements (e.g., b_3) coincides several times with the stimulus a_4 (the conditioning stimulus), it is remembered: a) the number of random mo-

tions (b_1, b_2 ... b_m) falls off sharply; b) the animal begins to perform the motion b_3 continually.

8. If the movement b_3 does not always coincide in time with the appearance of the stimulus a_4 (which reinforces this reaction), the animal begins to sense external signals (a_1 ... a_2 ... a_n) and perform the movement b_3 after these signals. If the appearance of some signal, e.g., a_3, coincides several times with the movement b_3 and with the appearance of the signal a_4, a new conditioned reflex is developed. The animal begins to perform the movement b_3 only after the signal a_3 (the conditioning stimulus) is applied.

Two links of a reflex chain are formed in this manner.

These rules are henceforth used in the development of more and more new reflexes. The new reflexes are now worked out on the basis of coincidence of random movements with signal a_3 or a_4. Each of the conditioning stimuli may become a "support" for the formation of new reflexes.

On the basis of these rules, the animal can figure out, one by one, the laws of his environment and thence work out new optimum programs for its activity that result in the acquisition of water and food and the satisfaction

of other needs.

The algorithm described above provides definite criteria for evaluating the usefulness of the activities pursued by the control system, as well as the usefulness of the information being fed into the brain. It also provides an opportunity for selecting and memorizing the useful movements and the reliable and useful information.

At first, the basic criterion for the validity and usefulness in this process is repeated time-coincidence of some new stimulus or motion with food; later, in the course of further formation of the system, this becomes the repeated time-coincidence of new movements or signals with one of the conditioning stimuli of the earlier links (conditioned reflexes) of the chain. This criterion is fully reliable, since the occurrence of repeated coincidence may serve as proof that the organism is dealing in this case not with random coincidence of two signals, but with a real law of the external world (criterion of certainty). At first, however, the information-usefulness criterion is repeated coincidence of new signals with food, and thereafter with a conditioning stimulus, which was, in turn, associated with food earlier.

This algorithm also provides for the emergence, in the "learning" process, of new guidelines which are

then used to evaluate the usefulness of the various movements and the importance of various bits of information. As we have already noted, such guidelines may be represented by any of the conditioning stimuli of conditioned-reflex systems developed earlier (a_4, a_3, a_2, etc.). It is important to note that the number of these stimulus-guidelines increases rapidly as the formation of newer and newer reflex systems advances in the animal. This, in turn, furnishes a requisite for the more rapid development of increasingly ramified conditioned-reflex systems. There is created a system of processes which are self-accelerated in the process of their own development. In the formation of new behavior patterns, the survey of the possible variants (b_1, b_2, b_3, ... b_3) need now continue not until the food appears, but up to the appearance of any of the conditioning stimuli of the reflex systems developed earlier (a_4, a_3, a_2). Thus we have the explanation for one of the characteristic singularities of the brain's operation as a self-organizing system: this consists in the fact that the capacity for further learning increases rapidly with learning.

On analysis of the facts detected in the investigation of various routes to the formation of conditioned-reflex systems, we may come to the conclusion that the

algorithms used by the brain also provide for a definite total number of rules determining the order and nature of the movements. In certain stages of the process, the animals carried out only one or two definite movements. During other periods, a large number of random movements occurred. The algorithm included definite rules according to which the moments of emergence and disappearance of the variant-survey phenomenon were determined. The definite rule sum also determines the nature of the new motions as functions of the results of the preceding "learning" period. Such organization and sequence in the nature of the disturbances that the animal applies to the environment is of great significance. It reduces the number of trials made by the animal.

A general examination of the description of this algorithm indicates that it can apparently, under certain conditions, provide for the development of a new program of the brain's operation.

However, we cannot regard this point as proven. Aside from the above, the question remains open as to the conditions under which this algorithm may prove effective, as does the question of the speed of formation of the new work programs, the number of necessary trials, and the dependence of these indices on various conditions.

A special automaton was built for study of these questions. The automaton is described in the sixth chapter of the present book.

The inference was drawn on the basis of study of this automaton that under certain conditions, the algorithms detected in the animal experiments may lead to the formation of a new program of operation of the brain.

One of the basic conditions necessary for the effective use of an algorithm consists in the requirement that various stimuli that can be sensed by the control system (a_1, a_2, a_m, etc.) appear from time to time in the external medium.

As we have noted, this condition may be met both in the work of the complex cybernetic machines that control the work of industrial enterprises and in study of the behavior of an animal under its natural living conditions.

The appearance of various stimuli in the environment may be caused by the unfolding in this medium of various processes; the result is that all possible variations will arise. They may also be due to the movements of the animal or to activities of the cybernetic machine that give rise to certain changes in the surrounding situation.

Thus the algorithm described may be embodied in

the technical control systems with which the operation of industrial enterprises is controlled and also serve as a basis for the development of new complex behavior patterns under the natural life conditions of animals. The effectiveness of application of this algorithm depends on a whole series of factors:

1) the probability of the appearance of the various stimuli in the environment and the duration of the time for which these stimuli act;

2) the speed of the control system's reaction;

3) the total number of motor reactions of which the control system is capable and the total number of stimuli that it can pick up from the external medium.

Let us consider a certain concrete situation in order to analyze the speed of development of a conditioned-reflex chain under different conditions.

Let the control system "A" have n different receptors capable of sensing various stimuli, and be capable of performing m different activities. At the same time, various stimuli may arise at random, with a certain probability P, in the external medium surrounding the control system.

Let us suppose that each of the stimuli can arise 10 times in the course of an hour and that its action is

terminated after ten seconds. It is necessary to develop the reflex chain $a_1 - b_1 - a_2 - b_2 - a_3 - b_3 -$ food.

For the first conditioned reflex to be developed under these conditions it is necessary that the stimulus "a_3" coincide several times with the animal's movement "b_3"; this would result in the acquisition of food.

General examination of the conditions of operation of the system indicates that the probability of this coincidence is not, in itself, very high. Thus the first stages of development of the reflex chain will proceed very slowly. However, an important singularity of the algorithm described is that the process of development proceeds with increasing rapidity as new conditioned reflexes are formed.

If the animal has already formed certain conditioned reflexes and a_4 and a_5 are the conditioning stimuli of these reactions, coincidence of the stimulus a_2 with food will not be necessary for development of the next conditioned-reflex reaction. The development may occur on coincidence of new stimuli with the signal a_5, with the signal a_4, etc. Thus the probability of the coincidence necessary for the construction of the new reflex reaction increases significantly. Here, the greater the number of conditioned reflexes developed, the higher will be the probability of co-occurrence of the two stimuli developing new conditioned reflexes. Thus we have a process

which goes faster and faster as it unfolds. W. Ross Ashby /59,60/ indicated the importance of studying such processes. He stressed that the detection of processes of this type in biological systems may result in solution of a series of vital physiological problems.

In addition to the algorithm described above, certain other algorithms were detected which may also play major roles in the formation of the conditioned-reflex chain.

One of these algorithms may be described as follows (algorithm No. 2):

In the development of the chain $b_1 - a_1 - b_2 - a_2 - b_3 -$ food

1. The animal performs random activities ($b_1 \ldots b_n$). In the event that some movement (e.g., b_3) coincides several times with food, this movement is memorized. Then the following changes in the animal's behavior are observed: a) the random movements cease; b) the animal begins to perform the motion b_3 continually.

2. If the animal now receives food each time, no further changes are observed in its behavior. If the animal does not get food after performing the movement b_3, the movement b_3 disappears. Together with this we observe a reaction associated with the appearance of numerous ran-

dom movements.

3. If none of the random movements b_3, b_4, b_8, etc. produces a change in the surrounding medium, these movements are given up. If some one of the movements, e.g., b_2, results in the appearance of some completely new (food-unrelated) stimulus a_2, an orientation reaction appears. This reaction is manifested in the animal's first performing the previously abandoned movement b_3.

4. Should food appear as a result of this movement, then the motion b_2 that produced the new stimulus a_2 as well as the stimulus a_2 itself are memorized.

5. The following changes in the animal's behavior are then observed: the random movements cease; the animal begins to perform the movement b_2 continually: This movement results in the appearance of the stimulus a_2. The stimulus a_2 produces the movement b_3 and the acquisition of food.

6. Thus two links of the reflex chain are found to have been formed at once. New movements are developed and new conditioning stimuli are cut into the system at the same time.

7. If this chain of reflexes leads to food, no further changes are observed. If it does not lead to food, the animal begins to carry out random movements.

8. If an entirely new stimulus arises as a result of some movement, the animal responds to this stimulus with the movement b_2 which it had previously abandoned. The further formation of a complex chain of conditioned reflexes may proceed on this principle.

Let us also present an operating algorithm (algorithm No. 3) based on orientational-exploratory activity. The chain of reflexes $a_1 - b_1 - a_2 - b_2 - a_3 - b_3 -$ food is developed.

1. The animal performs random movements ($b_1, b_2 \ldots b$) and variant sets of movements ($b_2, b_1, b_3, b_4, b_1; b_{15}, b_1, b_5$, etc.).

2. If no changes occur in the environment as a result of these movements, and new signals ($a_1, a_2, \ldots a_n$) do not appear, the testing movements are discontinued. Motor activity disappears altogether after a certain period of time.

3. If, however, some completely new indifferent signal ($a_1, a_2, \ldots a_n$) not related to food arises as a result of these motions, then the motions that disappeared earlier (b_1, b_2, b_3, b_n) reappear.

In addition, the motions that produced the new signal are remembered.

4. Thus a chain of reflexes is formed on the

novelty principle until this reflex chain accidentally results in the appearance of either food or one of the conditioning stimuli of the nourishment reflex system developed earlier. Then the entire system worked out on the basis of novelty reinforcement is stabilized.

This method of development has important shortcomings. The animals usually develop a reflex chain containing very many extraneous components rather than the chain $a_1 - b_1 - a_2 - b_2 - a_3 - b_3 -$ food. For example: $a_1 - b_{10} - b_{15} - b_1 - b_6 - a_2 - b_2 b_4 a_6 a_3 b_4 b_4 -$ food.

A special algorithm is used to bring this system into correspondence with reality.

The animal begins to eliminate various motions from the system one after another. For example, it follows not the chain $a_1 - b_{10} b_{15} b_1 b_6 - a_2 - b_2 b_4 - a_6 a_3 - b_4 b_3 -$ food, but the chain $a_1 - b_{10} - a_2 - b_2 b_4 - a_6 a_5 - b_4 b_3$.

1. If this shortened chain is reinforced by food, the dropped link $(b_{15} b_1 b_6)$ is not restored.

2. If food is not forthcoming, they reappear next time and another element of the chain is dropped. Thus all elements of the system are tested, one after another, to see if they are essential, and the extraneous ones are gradually "sifted out." In the end, only the necessary

chain $a_1 - b_1 - a_2 - b_2 - a_3 - b_3 -$ food remains.

The above algorithm No. 3, which is based on orientational-exploratory activity, may be used under conditions in which algorithm No. 1 would be ineffective, since it does not require the appearance of new signals. The animal itself gives rise to the appearance of these signals through its active movements. This algorithm has essential deficiencies, however. These consist in the fact that it does not provide an adequate system for evaluating the usefulness of the information entering the brain. The novelty of the incoming information is the reinforcing factor that provides for the development of new conditioned-reflex chains. As a result, the algorithm may lead to the development of a very large number of unnecessary reflex systems. This property of the algorithm determines the circumstance that it can be used only by systems that have considerable storage capacity. For example, it is present in dogs and absent in pigeons, and used only to a small extent by rats.

Under their natural living conditions, animals apparently use different algorithms in different cases. The simultaneous complex use of several algorithms in "studying" a new situation is evidently most rational. For example, in the case of complex application of algo-

rithms No. 1 and 3, the animals may use algorithm No. 1 to create a system for evaluation of the usefulness of bits of information, and then employ algorithm No. 3 to begin an active "investigation" of external laws. In this case the process of "investigation" will doubtless prove more fruitful, since it can culminate not only in the appearance of food (an unconditioned stimulus), but also on the appearance of any of the signals developed on the basis of algorithm No. 1 (the latter serve as guidelines).

This consideration of the progress raises the new question as to the existence of a system of rules (algorithms) of even higher order which determines the optimal sequence of application of algorithms No. 1, 2, and 3.

The animal apparently first develops a certain "most convenient" program for using the various algorithms on the basis of certain general features of the new situation; the process of "investigating" the new environment is effected through following this program. The question of the nature of these higher-order algorithms is highly important and should become the object of special investigations.

d) More Complex Forms of Information Processing

In the preceding chapter we analyzed the laws of operation of the brain which are related to the formation

of conditioned-reflex chains. However, the simple reflex chain is only one of the simplest forms of activity of the brain.

Under the natural living conditions of animals, they exhibit forms of behavior based on a considerably more complex conditioned-reflex system which integrates a large number of singularly interrelated simple conditioned-reflex chains. Here the execution of the individual reflex chains which form the overall system does not usually lead to the acquisition of food, but merely creates certain "pre-requisites" which make it possible for other conditioned-reflex chains to result in the satisfaction of this need under certain conditions in the future. Here the final reinforcement by an unconditioned stimulus in the form of the acquisition of water and food may be put off by a very considerable interval of time. For example, to obtain food under the natural conditions of its existence, a carnivore must track prey, catch it, and kill it, and only then is the direct unconditioned reinforcement achieved.

Thus in the natural living conditions of the animal we encounter the existence of so-called polyphase behavior, in which each of its stages creates only a "pre-requisite" for the execution of the following phases

of the behavior.

Study of the algorithms that form a basis for the development of these complex behavior patterns presents considerable interest.

As we have already noted, it is necessary in considering this problem to take into account the interaction between two interrelated systems.

One of these systems is the control system (brain), and the other system is the external medium or "the field of activity of the control system". Complex systems of interrelated processes obtain in the external medium.

In our examination of the problem formulated in the present chapter, we shall take into account the existence, in the environment, of systems of relationships which are more complex than those considered in the preceding chapter.

Included among the general cases is the case in which the presence of some factor inhibits the completion of a given process. As an example, we might mention the case in which the presence of some substance in the operation of a chemical enterprise operates as an obstacle to the unfolding of an entire cycle of chemical reaction. In this case, the problem of study of those algorithms in the control system which would make it possible to determine which substance is interfering with the process and

which would work out a new operating program leading to the elimination of this detrimental product acquires great significance.

The case in which the presence of two mutually independent components is found necessary for the accomplishment of a process may serve as another general case. In this case we encounter the problem of finding operating algorithms for the control system which would make it possible to identify each of the necessary components.

The complexity of this problem consists in the fact that the expediency and importance of one of the components may become evident only in the presence of the second component. The result is that evaluation of the value of the individual components becomes difficult.

The algorithm should, in addition, provide for the development of new operating programs which could provide for the acquisition of each of these components independently of the other. Here it is important to note that in contrast to the case of development of simple reflex chains analyzed above, the animal will not obtain confirmation in the form of food in developing new behavior patterns in this case, since the presence of one of the components is still insufficient for the appearance of an unconditioned confirmation.

It must be noted that we are considering a definite principle of the structure of systems of external laws. The external relationships themselves may definitely be much more complex in form; as an example, the system of laws governing the operation of a chemical enterprise may include systems of cause-and-effect relationships in which both of the principles described above (the principle of the presence of a substance which interferes with the reaction and the principle of the presence of two components) may appear repeatedly, combining with one another in a complex manner.

Study of the principles on which a control system placed under the conditions described above can work out optimal behavior patterns which take into account all properties of the complex laws of its external surroundings is of interest.

We have already noted that the development of a simple conditioned-reflex chain may be regarded as a process of detection of systems of external laws prevailing in the environment and construction of an isomorphic system constituting, as it were, a "copy" of the prevailing system of external relationships on this basis in the brain.

The problem presented in this chapter may be formulated as a problem of finding algorithms which will provide for the formation of more complex isomorphic systems

that are capable of reflecting more complex forms of interaction of the systems of external laws in their work.

The formulation of the problem given above is in good agreement with Ashby's system of concepts. He writes /59/ that "cybernetics is essentially concerned with study of cause-and-effect relationships, particularly in cases when they are represented by long chains of events in which the activity of each stage serves in turn as the cause of the following stage. In such cases we study the relation not of one cause to one effect but that of the whole group of causes to the group of effects that corresponds to them. Since the relation of cause to effect is most clearly observed in mechanisms of various types, the technique of cybernetics is readily applied to them.

Thus cybernetics is a part of the general science of dynamic organization".

We have discussed the question of the relationship of cybernetics to V.I. Lenin's reflection doctrine in a special article /16/.

Special experiments were carried out to study the problems formulated above. The technique of these experiments was similar in principle to the technique used for study of the laws of development of simple conditioned reflex chains. The difference consists in the fact that more

complex systems of external relationships (interrelationship between different signals) were created during the experiment in the external medium surrounding the animal. Specifically, systems of laws were created in which the presence of one stimulus made it impossible to carry out an entire chain of nourishment conditioned reflexes that had been developed previously.

Under these conditions, just as in the development of simple chains of conditioned reflexes, we observed a process of gradual formation of complex conditioned-reflex systems which reflected correctly the systems of external laws created artificially in the course of the experiment, and which made it possible for the animal to obtain food under these conditions.

The following important facts were observed: it was found that the animal was capable of identifying stimuli which prevented the execution of a conditioned-reflex chain, and also of identifying stimuli in cases when the simultaneous presence of several different signals was necessary for the acquisition of food.

The fact that new conditioned-reflex reaction chains can be worked out by the use of the disappearance of the stimulus which inhibits the completion of the nourishment reflex chain as a reinforcing factor is an important cir-

cumstance. These chains of conditioned reflexes are distinguished by the fact that they do not require reinforcement by an unconditioned stimulus (food) for their development, but are reinforced by the disappearance of the stimulus which prevented the completion of the nourishment chain of reflexes.

To use physiological terminology, this stimulus may be referred to as an inhibitory conditioned stimulus and the chain of reflexes based on it may be regarded as a "deinhibiting chain" of conditioned reflexes.

This chain of reflexes is included in the general complex of the nourishment reflex system as one of its components, and it vanishes, for example, when the animal is satiated or when the nourishment reflex system is not sustained by food. At the same time, it possesses a certain degree of "autonomy", since it can be separated from the basic nourishment chain by a considerable interval of time and does not have to be followed by reinforcement of food.

The food (the unconditioned reinforcement) is provided after completion of the entire conditioned-reflex system in which this "deinhibiting chain" occurs.

We detected certain laws related to the achievement of deinhibiting reflex chains. It was found that animals react to conditioned stimuli of deinhibiting reflex

chains only when the inhibitory conditioned stimulus on which the conditioned reflex chain in question was developed is applied. If the inhibitory conditioned stimulus was cut out, the animal did not react to the conditioned signals of the deinhibiting reflex chain even though this chain had been fully stabilized.

Thus we arrive at the conclusion that the structure of a conditioned-reflex system can not be reduced to a simple chain of successive conditioned-reflex reactions. Systems exist with a definite more complex structure which is related to the presence of a stimulus which we shall call the "switching-in" stimulus. Although this stimulus does not give rise to any specific motor reaction, it does set the entire chain of conditioned reflexes into operation.

We have already mentioned that certain principles of the structure of conditioned-reflex systems came to light in our experiments. In actuality, the systems which exist under the natural living conditions of the animals and are constructed on the basis of these principles may themselves be highly complex. Our experiments showed that the inhibiting reflex chain may develop its own "conditioned inhibition" on the basis of whose application an inhibiting second-category conditioned-reflex chain may be developed. This second inhibiting chain of reflexes may also

develop its "own" conditioned inhibition, the removal of which may serve as a basis for the development of a third inhibiting chain.

In study of this complex system, which consists of several chains of conditioned reflexes, we may detect the presence of a whole complex of "reciprocally subordinated" conditioned stimuli which trigger one another.

Let us present a scheme.

In this diagram, the conditioned switching-in stimuli are denoted by the different letters T_1, T_2, T_3.

The experiment indicated that the execution of the third inhibitory reflex chain is possible only in the presence of the three triggering conditioned stimuli: T_1, T_2, and T_3.

The triggering of the second inhibitory chain is possible in the presence of the two and only the two triggering stimuli T_1 and T_2.

We may, on the basis of the experiment draw the following conclusions concerning the algorithms of information processing in the brain which provide for the formation of more complex conditioned reflex systems.

Upon performance of algorithm number one, which we described earlier as leading to the development of the nourishment reflex chain (a_1-b_1-a_2-b_2-food) the following sequence of activities (algorithm No. 4) is carried out:

1. If the chain of reflexes leads to the acquisition of food in each case, then no further changes are made in the system of activities.

2. If the chain developed does not lead to the acquisition of food each time, the animal begins to sense external stimuli. Now, if the presence of some stimulus (for example T_1) coincides several times with the performance of the chain of reflexes a_1-b_1-a_2-b_2 and with the absence of food, then this stimulus is remembered.

3. After this, the following changes appear in the behavior of the animal:

a) during the period in which the stimulus T_1 is present, the animal does not respond to the conditioned signals of the previously developed chain of nourishment reflexes (a_1, a_2);

b) the animal reacts to these signals (a_1, a_2) during the period in which this stimulus (T_1) is absent.

4. If the stimulus T_1 occurs seldom and acts for insignificant periods of time, no further changes are observed in the behavior of the animal.

If the stimulus T_1 arises frequently and acts for a long period of time, a large number of random motor reactions arise. If one of these motor reactions, for example b_4, coincides several times with the disappearance of the stimulus T_1, this reaction is remembered.

5. Thereafter the following changes in the behavior of the animal are observed: the animal ceases all random motions. The motion b_4 which coincided several times with the disappearance of the stimulus is reinforced and repeated each time the stimulus T_1 appears.

Then algorithm No. 1, which provides for the development of a reflex chain leading to the disappearance of the stimulus T_1, is applied.

In another series of experiments, we created an external situation in which the appearance of food became possible only in the simultaneous presence of two mutually independent stimuli. Let us present a schematic representation of this situation.

The acquisition of food was possible only in the simultaneous presence of the stimuli a_3 and a_6. Food was not given to the animal in the presence of one of these stimuli alone. When the animal was placed under these con-

ditions, it was observed that it developed a reflex response to a complex stimulus which included the two components a_3 and a_6. The reaction was not executed in the absence of one of the components.

It is important to note the fact that the cutting in of one of the components of the complex stimulus (a_3 or a_6) can serve as a support for the development of a new chain of reflexes (a_1-b_1-a_2-b_2-a_3 or a_4-b_4-a_5-b_5-a_6). Just as was the case in the inhibiting chain of reflexes which we described above, these chains of reflexes were unnecessary in the process of development and reinforcement of the unconditioned stimulus. Only the application of one of the components of the complex stimulus (a_3 or a_6) could serve as a reinforcing factor.

In this manner it became possible to form complex reflex systems consisting of several "autonomous" conditioned-reflex chains. Here it was also observed that the chain of reflex reactions developed on the basis of reinforcement by one of the components of the complex stimulus (a_3 or a_6) was not carried out when this signal (a_3 or a_6) was cut in.

Thus in conducting this series of experiments we also came up against the existence of a special category of "triggering" conditioned stimuli, the presence of which

made it impossible to carry out the reflex reaction chain in question.

These experiments may be taken as a basis for the following conclusions concerning the algorithms at the basis of the development of complex conditioned reflex systems (algorithm No. 5).

1. If the simultaneous occurrence of the stimuli a_3 and a_6 coincides several times with the acquisition of food, but each of these stimuli taken alone does not coincide with the acquisition of food, then a conditioned response to the complex stimulus is worked out.

The behavior of the animal varies as follows: a) in the simultaneous presence of the two stimuli a_3 and a_6, the animal performs a motor reaction; b) in the presence of one of the stimuli, the motor reaction is absent.

2. In cases where coincidence of the stimuli a_3 and a_6 occurs frequently, no further change is observed in the behavior of the animal. If, however, the stimuli a_3 and a_6 rarely occur together, a reaction involving the appearance of random motions arises.

3. Then, if one of the randomly executed movements, e.g., b_2, coincides several times with the appearance of one of the stimuli, e.g., a_3, then this movement is remembered and the following changes occur in the behavior of

the animal: a) all random movements cease; b) the motion b_2 arises immediately in the absence of the stimulus a_3. Then algorithm No. 1 is applied.

A new reflex chain which leads to the appearance of the stimulus a_3 is worked out on the basis of this algorithm.

The algorithms described above may provide for the formation of complex behavior patterns in the animals under different environmental conditions. The result is behavior which consists of a whole series of autonomous conditioned reflex chains (polyphased behavior).

CHAPTER V

STUDY OF THE LAWS OF FORMATION OF NEW BEHAVIOR PATTERNS ON THE BASIS OF PROCESSING INFORMATION ACCUMULATED EARLIER

One of the important singularities of the work of the brain as a highly perfected system is its capacity to form a new system of conditioned reflexes (new behavior patterns) on the basis of processing information which was accumulated earlier and stored in the memory in connection

with new information arriving from the environment.

When an animal encounters new environmental conditions and when new needs arise, we observe a new behavior pattern which on the one hand is appropriate to the nature of the situation and on the other hand results in satisfaction of the animal's requirements. Here the emergence of the new behavior pattern occurs immediately without any supplementary development based on the use of experience accumulated previously. In these conditions, however, we speak of the formation of "purposive" or "reasonable" behavior. Here it is important to note that the behavior of the animal invariably amounts to a reaction to the entire complex of stimuli acting on the nervous system in the situation in question.

The behavior of the animal cannot be regarded as the sum of its responses to the set of stimuli which have been applied, but is the result of complex processing of information which was accumulated earlier and stored in the memory, in association with new information arriving from outside. The study of this phenomenon is of great interest to cybernetics.

Recently, the creation of automatic control systems that will be capable of using information accumulated earlier in new situations to adopt new purposive solutions

which lead to the attainment of a useful effect has acquired pressing importance.

Let us consider certain problems which arise in the study of this problem in its general form.

Suppose that a certain control system "A" can perform various activities: $b_1, b_2, b_3, \ldots b_n$, and can receive certain items of information $(a_1, a_2, a_3, \ldots a_m)$ from the external medium.

This system has a certain store of information in the form of the--conditioned reflex systems developed earlier: $a_{12}-b_8-a_1-b_1-a_3-b_2$, etc., and there is some concrete situation (a complex of stimuli entering the system) a_1, a_4, a_8, etc.

Under these conditions, the system is faced with the problem of developing a new operating program by means of which it will be possible to obtain some result "K". Here it is important to note that although all of the signals arriving from the controlled object (the environment) are already known to the control system and form parts of the various operating programs composed earlier, the actual combination of these signals may be entirely new.

As a result of the control system's work, there should arise some new optimum behavior pattern appropriate to the specific situation (a_1, a_4, a_8) and leading to the

attainment of the defined goal (K). In other words some new purposive form of behavior should be worked out.

This new operating program obviously develops on the basis of processing of information accumulated earlier. In the course of this processing, information which, first, can be of use for the attainment of the goal K and, second, can be applied to the specific situation, must obviously be selected from the entire mass of information stored in the memory.

In solving the problem of the algorithms capable of processing information in this way and the problem of the physical realization of these algorithms, it must be remembered that in the case under consideration, the control system is to a considerable degree formed in the learning process. This leaves its imprint on both the very organization of the system and on the pattern observed in the retention of information.

As we have already noted, the information appeared to be stored in the form of a large number of operating programs which vary greatly in character and were developed at different times.

It is obvious that in the process of working out a new behavior pattern, certain processes involving the separation of various segments from the different operating

programs developed previously and combining these segments to form new systems must be carried out.

a) Technique of Investigation

For study of this problem, it was necessary to work out special systematic procedures which permitted the study of the laws of operation of a system having a certain store of information in various situations. The experimenter must have exact knowledge of the nature of the information stored in the memory and the nature of the newly-arrived information.

For this purpose we used a technique involving experimentation on animals in which certain complex reflex systems had been developed earlier. This technique permitted study of the operating algorithms of the brain under conditions in which the animals already possessed partial or complete information concerning the experimentally-created environment. These algor provided for the seeking out and memorizing of the necessary information and for complex mechanisms of processing this old information in association with the new information arriving from the environment. Here, obviously, comparison and regrouping of information of various types is of great importance.

Complex systems of nourishment motor conditioned

reflexes, the technique of development of which has already been described, were developed in the animals. In addition to this, a water-reinforced chain of drinking reflexes was also developed. If the animals were hungry and not thirsty, they would carry out the chain of food reflexes and would not respond to the conditioned stimuli of the water chain. If the animals were satiated and then were made thirsty, they would react only to the conditioned stimuli of the chain of drinking reflexes. The animals were fed to satiation in the course of the experiments. The excess quantity of food remained in the trough. The dogs were then allowed to become very thirsty. Different complexes of the conditioned stimuli of the nourishment reflex system were applied while none of the signals of the drinking chain was administered. Here it could be observed under certain experimental conditions that the animals developed new behavior patterns which integrated individual segments taken from various parts of the food and water conditioned-reflex systems. The new behavior could not be reduced to a simple sum of responses to the set of signals administered. In every case, the animals responded selectively to one conditioned signal of the reflex systems developed earlier and did not respond to other conditioned stimuli.

When we applied different complexes of signals we

invariably observed a redistribution of the activity of the conditioned reflexes of the previously developed system which was characteristic for the given case. The phenomenon of selective activity is of great significance, since it testifies to the presence of certain processes in which information accumulated earlier is processed. It is important to stress that study of the process of appearance and disappearance of the activity of individual conditioned-reflex reactions under various conditions places in the hands of the experimenter an indicator that can be used in study of the brain's operation. The new behavior patterns arose immediately in the animals, without any additional development as a result of complex information processing in the brain.

In conducting the experiments, we knew exactly both the nature of the information accumulated earlier (of the conditioned-reflex systems developed earlier) and the nature of the information being fed into the brain for the first time (the new signals). We were also able to follow the process of formation of new conditioned-reflex systems. We noted from which of the previously-developed conditioned reflex systems and under which conditions the various segments were taken and used in the construction of a new behavior pattern. By varying the form of the experiment and

by administering various complexes of stimuli, we were able to follow the processing of the information which had been accumulated earlier and the information being fed to the brain for the first time. Thus the method being described here made it possible to detect certain algorithms in the brain's operation which provided for the formation of new forms of purposive behavior in new situations.

The appearance of "selective" activity of certain conditioned-reflex reactions was an objective index to certain information-processing mechanisms at work in the brain. Here certain relationships which characterize this phenomenon were detected.

On the appearance of a new requirement, e.g., first, certain elements of those reflex systems which are directly related to the acquisition of water (the chain of drinking reflexes) become active. In this process the activation begins, as it were, to propagate sequentially through these systems. The individual segments of the system passed into the active state one after another.

If in those segments of the system which were activated there was at least one stimulus which was simultaneously present in the environment, the corresponding reflex reaction would emerge. If, on the other hand, there was no such coincidence of two identical signals, then the

process of successive activation of previously-developed reflex systems would continue, propagating from one system into another. The pattern described here provides a basis for certain conclusions with respect to the ways in which the brain processes information. It becomes clear that information accumulated earlier may be taken from the memory and used in the formation of new behavior patterns. Here we discern certain rules which determine the use of old information. These rules include the necessity of activation of various parts of the system, as well as the necessity of the presence of the same stimulus in the active section of the reflex system and in the environment. Here there is no process of comparison between accumulated information and newly arrived information.

This technique also makes it possible to cast light on the role played by the special system of "triggering" stimuli. The appropriate part of the reflex system could not become active without the presence of some triggering stimulus. This phenomenon is of great importance; it provides for selectivity of the process of "scanning" of the previously-developed reflex systems (previously-accumulated information) in searching for the necessary information and makes this process dependent on the presence of certain signals in the environment. Due to the presence of this

mechanism the search for complex information in the brain does not involve scanning all of the information stored in the memory, but only the inspection of a small part of it — namely, the part which can prove useful in the given situation.

b) Laws of Processing Previously Accumulated and Newly Arrived Information

The following results were obtained as a result of conducting the experiments: When the animal did not experience hunger or thirst in the course of the experiment, it would not respond to the conditioned stimuli of previously developed conditioned-reflex systems. When it was made thirsty, conditioned responses to certain conditioned stimuli appeared. Here, the appearance of activity of the individual conditioned-reflex reaction was selective in nature. First to become active were the conditioned stimuli of conditioned-reflex chains which were directly related to the acquisition of water (the chains of drinking conditioned reflexes). Here, in turn, those conditioned reflexes of the chain which were closest to the unconditioned reinforcing factor were first to become active.

In the event that the corresponding conditioned stimulus was present in the environment simultaneously with the activation of a reflex chain, the conditioned re-

flex reaction occurred. Then no other reflexes of this chain passed into the active condition. If, however, there were no conditioned stimuli, the process of successive activation of the different conditioned reflexes in the previously developed systems continued further development.

An important singularity characteristic of the development of this process consisted in the fact that in cases of the presence of the same stimulus in two different conditioned-reflex systems (e.g., the drinking and feeding systems; the feeding and defensive systems), conditioned-reflexes of the other reflex chain (for example, the system of feeding conditioned reflexes) would proceed to become activated beginning from the point at which the common stimulus occurred. This would be followed immediately by successive "activation" of this second (feeding) reflex chain.

In cases in which stimuli of the feeding reflex system were not present in the environment, but a stimulus in the feeding reflex system was the same as one in the defensive reflex chain, then a process of successive activation of the various conditioned reflexes of the defensive chain would occur.

On the basis of these experiments we may draw the following conclusions as to the character of the informa-

tion-processing algorithm that forms the basis for the development of new behavior patterns (algorithm number 6).

1. On the appearance of thirst, a process of scanning previously-developed chains of drinking conditioned reflexes begins. Here, the stimuli of these chains are successively compared with stimuli present in the environment at the moment of time involved. If matching is detected, a reflex reaction appears and the process of scanning of the reflex chains is discontinued.

If no similarities are detected, the process of inspection continues on an increasingly broader scale, embracing more and more of the conditioned reflexes of the previously developed chains.

2. If no conditioned stimulus of the drinking conditioned-reflex chain is present in the environment, and the drinking and feeding chains have a common conditioned stimulus, we observe the beginning of a process of inspection of the feeding-chain stimuli beginning from the point at which the common stimulus occurred. Here, the stimuli of the feeding chain are also compared with stimuli in the environment. In the event that coincidence is observed a reflex reaction arises.

3. If there is no coincidence and there is a stimulus common to the feeding and defensive chains, inspection

of the defensive chain of reflexes begins, and so forth.

The algorithm described above may result in a combination of segments from different systems of previously-developed conditioned reflexes to form new functional complexes.

The principle of this combination is indicated in the diagram below.

$a_1 - b_1 - a_2 - b_2 - a_3 - b_3$ — cessation of pain;

$a_4 - b_4 - a_5 - b_5 - \boxed{a_3 - b_6} - a_7 - b_7$ — food;

$a_8 - b_8 - a_9 - b_9 - \boxed{a_7 - b_{10}}$ — water.

As a result of execution of this algorithm there occurs a process of consecutive comparison of the accumulated information with information arriving from the environment, as a result of which it becomes possible to detect conditioned-reflex chains which correspond to the character of the external situation.

It is important to stress that the result of performing the information-processing algorithm described above is the emergence of just such behavior forms which on the one hand result in the attainment of the goal set before the system, and on the other hand correspond exactly to the character of the external situation.

Exact correspondence of the newly-developed behavior patterns to the assigned goal is provided by the

fact that the process of inspection of previously-accumulated experience begins from those nerve elements which correspond to the nature of the assigned goal (thirst). Thus, this inspection encompasses only those reflex systems which can lead to the acquisition of water. On the other hand, correspondence of the newly-formulated behavior to the external situation is provided as a result of the process of comparison of the external information with the conditioned-reflex systems developed earlier.

In the process of forming a new behavior pattern, information which, on the one hand, can result in attainment of the goal placed before the system, and corresponds on the other hand to the conditions of the environment, is selected from the entire mass of information stored in the memory of the brain. Here, the selection is carried out twice: First those chains of reflexes are selected which can prove useful in the attainment of the goal placed before the control system, and then the small number of chains which are appropriate to the external situation are selected from among these.

It is important to note that it proceeds from our experiments that in the formation of complex behavior patterns in the brain, the inspection does not extend over all of the information stored in the memory. The inspection

of the information is strictly selective in nature. An insignificant fraction of the information that has been accumulated in the course of the individual lifetime of the animal in question is inspected each time.

Study of the question of the limits of applicability of the algorithm described above and its effectiveness under various conditions of the brain's operation are of great interest.

By way of answering this question, let us examine a certain system that has a certain reserve of information in the form of conditioned-reflex chains which were developed earlier.

Let us assume that this control system can carry out n different activities (b_1, b_2, $b_3 \ldots b_n$) and sense m external stimuli (a_1, a_2, $a_3, \ldots a_m$) and that the system contains a certain store of information which may be written in the form of the scheme:

$a_8 - b_3 - a_6 - b_1 - a_4 - b_2$ – water;

$a_3 - b_{10} - a_{15} - b_{16} - a_4 - b_{21}$ – food;

$a_8 - b_6 - a_{15} - b_{31}$ – disappearance of painful stimulus.

Let us suppose that the animal is hungry and the signal for the feeding reflex chain is not present in the environment. In this case, in accordance with the algorithm described above, processes of comparison of signals

of the feeding reflex chain with signals of another conditioned-reflex chain should arise in the system.

Let us consider the problem of the probability of the presence of the same signal in different systems together with the problem of the time necessary to detect coincidence, taking into account that if coincidence is not found during inspection of one system, a sequential process of inspection of other conditioned-reflex systems should begin.

The duration of the search will depend on the values of "n" and "m", i.e., on the number of signals arriving from the environment and the number of possible activities of the control system. The larger the values of "n" and "m", the greater will be the variety of the previously developed conditioned-reflex systems and the lower will be the probability of coincidence of identical stimuli in two different reflex systems.

Under conditions in which "n" and "m" are small numbers, the algorithm described may prove to be inapplicable. However, in cases where "n" and "m" are large numbers, the search for a moment of coincidence may occupy a very long period of time and this algorithm may prove useless.

Consideration of the "depth of search" in the

memory system is also of great interest. As we have already noted, when no coincidence occurs between signals of the feeding reflex chain and signals existing in the environment, the process of comparison of signals of this system with those conditioned reflexes which are present in other conditioned-reflex chains should begin. In practice, this process may continue for an indefinite period. Here, the longer (deeper) this process develops, the greater will be the number of stimuli that are compared with one another. This process may prove to be expedient within certain narrow limits, but it will obvioulsy become inexpedient at a certain stage in further searching, since it will require a great deal of work on the part of the brain and the expenditure of a great deal of time.

A general consideration of the problems set forth above leads us to the tentative conclusion that the algorithms described above may prove expedient under certain narrowly restricted conditions of the brain's operation. They may prove effective in certain species of animals and ineffective in other species of animals.

Among other things, this is indicated by the fact that these algorithms have been detected in clearly expressed forms in experiments on dogs and white rats.

They appear in very primitive form in experiments

on birds and are totally absent in turtles.

It was also possible in experiments with animals to detect other algorithms which mark out other ways to solution of the problem. For example, it was found in experiments carried out with rats that when two simple conditioned-reflex chains of different types were developed, the combination of segments of these chains into a new complex on the basis of the presence of a single common stimulus in these chains could be observed.

Such combination was not observed in more complex experiments. Regardless of the presence of a commom stimulus in the feeding and drinking chains, an animal which was experiencing thirst would not react to conditioned stimuli of the feeding reflex system.

The use of the feeding conditioned-reflex chain to acquire water (combination of two sections of different reflex chains) was not observed. Together with this, a reaction associated with the appearance of a large number of different types of random motions on the part of the rat (a reaction of inspection of different variants) emerged.

The following experiment was carried out: When the animal felt hunger and thirst the feeding conditioned-reflex chain was brought into operation in the course of

experiment. In absence of this chain, the stimulus which was also present in the drinking conditioned-reflex chain made its appearance. Although the animal did not obtain water in the course of this experiment, the capacity of the brain to combine sections of the feeding and drinking conditioned reflex chains on the principle of the presence of a common stimulus was detected on the following day.

It must be concluded that the drinking reflex chain which was not realized in the course of our experiments was in some sort of active condition, as a result of which the appearance in the environment of one of the stimuli of this chain was detected by the animal and served as a basis for subsequent unification of the two chains of conditioned reflexes.

The following conclusions concerning certain algorithms of the brain's operation may be drawn on the basis of these experiments.

When algorithm number 6 has been carried out and has not led to the acquisition of food the following changes arise: a) Inspection of previously developed reflex systems is discontinued; b) there arises a reaction involving the appearance of numerous random motor acts; the nervous elements corresponding to the conditioned stimuli of the drinking reflex chain are kept in their

active condition (A. A. Ukhtomskiy's dominant-excitation condition /62/).

If one of the stimuli of the drinking reflex chain arises as a result of a movement of the animals, this movement or complex of motor reactions is remembered. A new behavior pattern may be erected on this basis.

In this case, therefore, the search system associated with inspection of information accumulated earlier is combined with the search system realized by means of motor reaction directed toward a change in the surrounding external medium.

The question of the expediency of the algorithm described and the limits of the conditions under which it can lead to a useful result may be answered on the basis of an analysis similar to that which we presented above. We shall not present a detailed discussion of the problem. The tentative conclusion that the described algorithm is expedient only under certain conditions and as applied in certain species of animals may be drawn on the basis of certain general considerations. One indication of this is the fact that in higher animals (dogs), this algorithm is expressed to a lesser extent than in white rats.

It was found as a result of the investigations

described above that the presence of a given system of reflexes in the animal does not, as a rule, in itself provide for the emergence of appropriate behavior. Under normal conditions the animal does not respond to the conditioned stimuli which are included in these systems. The action of some triggering stimulus is necessary if a certain form of behavior is to arise. Only then does a specific behavior pattern begin to form about this stimulus (goals).

This point is of great importance. Under their natural living conditions, animals usually form excessively large numbers of systems of conditioned-reflex reactions. Innumerable stimuli are present at all times in the environment. If the animal reacted at all times to all of these stimuli its behavior would become a chaos of continual and unrelated movements. This, however, is not observed. The behavior of animals is purposive.

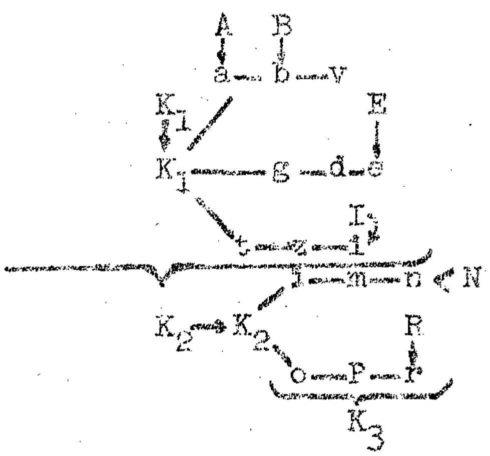
At any given moment of time animals react only to a definite narrowly bounded circle of stimuli and do not react to all other conditioned stimuli. Without the above capacity to react selectively to only certain definite environmental stimuli (namely, just those stimuli which are necessary under the conditions) it is impossible to imagine purposive and efficient behavior.

At the basis of this phenomenon we find the formation in the animal of complex conditioned-reflex constructions which possess special systems of mutually subordinated "triggering" and "cut-off" stimuli which in turn activate various reflex chains. Here the principles of organization of reflex systems set forth above, which are associated with the existence of additional side chains of reflexes leading to the attainment of intermediate goals, are of great value. Such a system provides for the development of purposive behavior.

Here we must also stress the significance of the fact that different reflex chains develop on the basis of their reinforcement with food, water, etc., then lose their specific value. When a new need arises, they are used immediately to satisfy it. This phenomenon is of very great significance. If there were a special and specific reflex chain at the roots of each of the numerous behavior patterns of the animal, an exceedingly large memory capacity would be required. A system which permits the use of old experience under various new conditions is considerably more economical with respect to the number of working elements required. Such a system must, however, possess specific mechanisms which provide for a memory search and for processing of the necessary information.

In connection with this problem we feel it important to mention certain specific properties related to the storage and location of information.

We must first emphasize the significance of a definite system, a definite organization in the storage of information. This structure may be represented in its general form as a highly branched system which combines interconnected reflex chains in a singular manner.



In this diagram, the upper-case letters denote various environmental stimuli (E, I, N, R, K, K_2, and so forth). The lower-case letters denote the corresponding cells of the receptor zone of the cerebral cortex, and K_1, K_2, and K_3, are triggering conditioned stimuli.

This diagram does not pretend to be an accurate reflection of reality, but it does permit clearer visualization of certain principles of the system's structure.

Characteristic properties of this structure are, first, its tree-like branched structure and second, the presence of systems of triggering stimuli of different categories (K_1, K_2, K_3, etc.).

It may be supposed that the process of propagation of an excitation wave over the system of nerve connections and the phenomenon of addition of excitations in the nerve cells is of great significance in the search for the necessary information in the memory system. Let us consider this phenomenon. As we have already noted, the animal does not under normal conditions respond to the conditioned stimuli included in this system (A, B, M, N, etc.). For any reflex activity to arise, it is necessary that one of the triggering conditioned stimuli appear (K_1 or K_2, etc.). This is denoted on our diagram by the letter K_1. When this stimulus acts, an excitation wave arises at the point K_1, and begins to propagate through the entire system of conditioned-reflex connections with which the point K_1 is connected. The result of this process will depend on whether the corresponding external stimulus, D, G, or A, is present at the given moment of time in the environment. If such a stimulus is present a process of summation of excitations is effected in the corresponding nerve cell and a motor reflex reaction arises. If, however,

there is no such stimulus, the reflex response does not arise and the excitation wave begins propagation through other structures.

It may also happen that the conditioned stimulus (I) is present in the environment but that the conditioned inhibitor (K_2) which prevents the performance of the reflex chain T--Z--I is also present simultaneously. In this case, an excitation focus is created at point K_2, just as it was at point K_1 earlier. This excitation begins to propagate through the systems of connections L--M--N and O--P--R. The result is the formation of behavior which leads to the removal of the conditioned inhibitor (K_2). If, however, a new conditioned inhibitor (K_3) stands in the way, the process continues further on the same principle. In our consideration of this scheme it is necessary to note that it provides for rapid location of the necessary information. The back-tracing process accomplished in the system in the course of propagation of the excitation wave over the systems of conditioned-reflex connections encompasses only a certain very small part of the "memory" --namely, that part of it which is associated with the triggering stimulus (K_1). Here, the system of triggering stimuli K_1, K_2, K_3, etc. which create, as it were, a specific system of subordination, are of great significance.

As a result, the process of irrational (idle) tracing is reduced to a minimum.

Nor is it difficult to see that as a result of propagation of the excitation wave through the system of previously-developed connections and the phenomenon of summation in the nerve cells, there has been effected a comparison of the external information entering the brain with the system of previously-formed nerve associations, as well as a process of re-combination of systems of previously formed associations.

As a result, behavior which corresponds exactly to the environmental conditions and leads to attainment of the necessary goal is formed in each case. In the formation of this behavior pattern, the organism obtains large quantities of external information and here, as it were, the brain actively selects this information. In any given moment of time it responds only to a definite, strictly limited group of external stimuli.

It must also be noted that a large number of different behavior patterns may be formed on the basis of a single system of conditioned reflex associations, in accordance with the conditions in the environment.

c) The Study of More Complex Information-Processing Patterns

Finally, we must consider a case in which the

formation of a new operating program for the brain is determined not by one but by several conditions. As in the case considered above, the emergence of a new external situation and the appearance of a new goal in the operation of the control system serves as a basis for the formation of new behavior patterns. The essential difference consists in the fact that together with the necessity of obtaining a definite goal, the control system must take into account the necessity of avoiding certain situations which may prove detrimental to it in its formation of the new behavior patterns.

Such conditions may be encountered very frequently both in the life of animals and in the operation of the various machines which control the work of industrial enterprises.

Under the natural living conditions of organisms, it is very frequently necessary to find a behavior pattern which will lead to the satisfaction of some requirement (acquisition of water, food, etc.) and at the same time to avoid situations which may present a threat to the life of the given individual, as well as to avoid painful stimuli in performance of the new behavior pattern.

Conditions for the avoidance of certain situations which might lead to breakdown or damage of the equipment

during the formation of a new operating program can also be established in the operation of control systems.

In this case the control system must possess new capabilities which must enable it, when a new expedient behavior pattern has been formed, to "foresee" all possible secondary consequences to which the performance of this behavior pattern may lead; it must be capable of forming new behavior patterns which will be able to hold the useful effect of the behavior unchanged and at the same time exclude the possibility of the appearance of negative (painful) effects.

The following experiments were carried out for study of this problem: Several different systems of conditioned reflexes, one of which involved the application of a painful stimulus, were developed in animals (dogs and rats).

Let us present the diagram of this system of conditioned reflexes.

$$a_3 - b_3 - a_1 - b_1 - \left.\begin{matrix} a_2 \\ \\ a_4 \end{matrix}\right\} \begin{matrix} -b_2\text{—food;} \\ \text{painful stimulus;} \\ \end{matrix}$$

$a_5 - b_5 - a_6 - b_6$—elimination of a_4;

$a_7 - b_7 - a_1 - b_8$—water.

It will be seen from the diagram that a nourish-

ment reflex chain was created in the animal in addition to certain defensive reflexes. Here, the conditioned signal for triggering of the painful stimulus was a complex of stimuli consisting of the two stimuli a_4 and a_2. One of the components (a_2) of the stimulus complex was connected into the nourishment reflex chain. Thus, if the stimulus a_4 was present in the environment, a situation was created in which the animal itself actively triggered the stimulus a_2 in the process of performing the nourishment reflex circuit, with the result that conditions were created in which he received a painful stimulus. Then a reflex chain was worked out to eliminate the painful stimulus. This conditioned-reflex chain was reinforced by elimination of the signal a_4. In addition to this a drinking conditioned-reflex chain which had one stimulus (a_1) in common with the nourishment conditioned-reflex chain was developed.

The experiment was conducted as follows: The animal was allowed to become hungry and given an excessive quantity of water (a dish with water was present in the chamber); under these conditions the following experimental situation was created: The signal a_4 (one of the components of the complex painful-stimulus signal) and the signal a_5 (the conditioned-stimulus of the chain which

triggered the signal a_4) were administered. The animal did not respond to these stimuli. Then after a certain interval of time the stimulus a_7 (the conditioned stimulus of the water conditioned-reflex chain) was applied. These conditions created a definite situation which the animal was encountering for the first time. This situation was characterized by the fact that by combination of the drinking and feeding reflex chains on the basis of the presence of a single common stimulus (a_1) it was possible to form a system of reflexes by means of which the animal could obtain food. In order to obtain food it was necessary for the animal to respond to stimulus a_7, but at the same time this situation was characterized by the fact that the animal itself had to trigger a painful stimulus in the process of performing the reflex chain.

The experiment showed that administration of stimulus a_7 did not evoke the corresponding reflex reaction, but gave rise to a completely different effect. Instead of carrying out the reaction to a_7 upon application of this stimulus, the animal exhibited the reaction to the stimulus a_5 (the conditioned stimulus of the chain of reflexes that eliminates the signal a_4).

The result of this was the accomplishment of a conditioned-reflex chain which led to the elimination of

one of the components (a_4) of the complex painful-stimulus signal. Thereafter, the animal would react to the stimulus a_7 (the conditioned stimulus of the drinking reflex chain) and, having created a composite conditioned-reflex chain, would obtain food. Thus it found a method to obtain food without experiencing the painful stimulus in the process.

It must be remembered in analyzing the results of this experiment that the situation described above had been created for the first time in the animal's experience. Therefore, the expedient solution of the problem which emerged was a product of complex analytic-synthetic activity of the brain. Each of the three conditioned reflex chains enumerated above was developed independently of the others, and they were combined for the first time under the conditions of this experiment.

The experiment described above indicates that the brain possesses a complex mechanism which permits it to form new behavior patterns on the basis of previously accumulated experience, taking into account a whole series of factors; the experiment also opens a way to scientific analysis of this phenomenon. It must be noted, however, that the algorithms described above in relation to the propagation of excitation across systems of previously

developed conditioned-reflex associations cannot fully account for this phenomenon.

It may be assumed that once the definite behavior pattern was formed, a new process complex was realized which permitted the animal to foresee all possible negative results to which this behavior might lead and to work out reaction patterns by means of which these negative consequences could be eliminated. The questions concerning the algorithms and physiological mechanisms forming the basis of this phenomenon are as yet for the most part unclear. Further work is necessary in this respect.

CHAPTER VI

SIMULATION OF THE LEARNING PROCESS

The present chapter is devoted to a description of an automatic device created with the assistance of the authors of the book on the basis of study of certain principles of the operation of the brains of animals.

This was done with certain purposes in mind — in particular, the verification of certain conclusions drawn as a result of conducting experiments with animals.

a) Formulation of Problem.

The Formal Neurons of MacCullough and Pitts

Simulation of the learning process has attracted the attention of many scientists over a long period of time. The first attempt in this direction was probably the "turtle" of Grey-Walter. However, the "conditioned reflex" that could be developed in the turtle seemed too artificial.

The conditioned reflex has also been simulated on general-purpose computers. This course of action permits only superficial statistical study of the reflex.

As far as we know, no attempt has as yet been made to develop complex conditioned-reflex chains.

The automatic device to be described represents such an attempt. Simulation of conditioned-reflex development with the general purpose computer is possible but not as interesting, since no hypothesis concerning the actual mechanism of reflex development is advanced. By creating an automaton specifically for the purpose of studying the mechanism of formation of complex reflexes we may propose a series of hypotheses concerning the neurophysiological mechanism of their formation.

The description of the automaton will be given as follows: the scheme will first be constructed using the formal neurons of MacCullough and Pitts and then certain

schematic diagrams in accordance with which the actual automaton was constructed will be given.

The MacCullough and Pitts concept of the nerve network was presented above (Chapter II). Here we shall consider the general-purpose element — the formal neuron of which the MacCullough and Pitts nerve networks analyzed in Chapter II consist — in greater detail.

On the basis of certain assumptions, MacCullough and Pitts /41/ arrived at the conclusion that a simplified model of the neuron — the formal neuron — could be used in analysis of logical networks. This neuron consists of a body or soma. One or more terminal plates of other neurons may be applied to the body of the neuron; these excite it. The terminal plates may be exciting or inhibiting in nature. The interval separating the body and the terminal plates is called a synapse. Nerve filaments (axons) which terminate

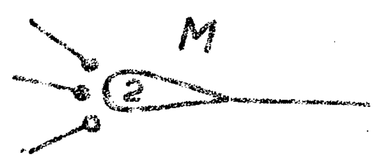


Fig. 1. The formal neuron.

in similar terminal plates extend from the body of the neuron.

Each neuron is characterized by a number h — its threshold. The threshold is the minimum difference between the numbers of exciting and inhibiting plates which results in excitation of the neuron.

We shall represent the neuron as shown in Fig. 1. Exciting plates are denoted by dark circles and inhibiting plates by open circles. The number which characterizes the threshold will be written in the body of the neuron, For the neuron M (Fig. 1) the threshold is two; this means that for the neuron to be excited it is necessary that two exciting plates or one inhibiting and three exciting plates, etc., be excited simultaneously.

b) Simulation of the Simple Conditioned Reflex

Let us turn now to the structure of the automaton. The first problem that arises in simulating the learning process is that of simulation of the simple conditioned reflex.

We shall consider the automaton in interaction with an environment. The environment will be described by a set of stimuli. Let us denote them by $I_1, I_2, \ldots . I$. The automaton will be described by a set of actions (reactions to external stimuli) $a_1, a_2, \ldots . a_n$. The activities of the automaton are directed toward a definite goal — the acquisition from

the environment of the sustenance N (unconditioned stimulus). It is possible, of course, to characterize the medium by means of a set of unconditioned stimuli (in a real medium, food, water, etc.). In constructing this automaton, however, the problem was simplified and studied without a single unconditioned stimulus.

In any real situation (medium), acquisition of the sustenance N requires the performance of a definite sequence of activities, each of which is evoked by a certain stimulus; the appearance of this stimulus is a confirmation of the correctness of the preceding activity, i.e., a reinforcing factor. In this manner, each concrete situation is described by a chain of the form:

$$I_1 - a_e - I_m - a_q - \ldots I_s \ldots - a_p - N,$$

where I_k are the external stimuli; a_k are the activities of the automaton; N is the goal (the unconditioned stimulus).

The automaton's learning process proceeds backward, i.e., a simple conditioned reflex is formed first:

$$I_s - a_p - N.$$

Then the stimulus I_s is in turn reinforced in developing the next link of the chain, since it is now directly related to the unconditioned stimulus N through the activity a_p. To obtain the sustenance N (for example, food for the animal) it is sufficient to perform the activity a_p

on the appearance of the stimulus I_s.

However, the external conditions may change and the medium may not respond with the appearance of the unconditioned reflex when the stimulus I_s evokes the response a_p. Then, obviously, the automaton should "forget" this reflex in order to develop a new one which is useful in this situation. This point was not taken into consideration in Walter's "turtle", since the latter embodied no reinforcement concept. However, it was observed in the experiment on the general-purpose computer.

Let us turn to the problem of simulation of the simple conditioned reflex.

Let us place a receptor neuron of the automaton into correspondence with each external stimulus $I_1, I_2, \ldots I_n$.

The problem consists in the following: if, on the appearance of the stimulus I_s (the receptor neuron I_s of the automaton is excited), the automaton responds in a random manner with the action a_p, and the sustenance N appears, and this occurs several times, the automaton should always respond to the appearance of the stimulus I_s with the activities a_p.

Let us consider the diagram of Fig. 2. This diagram will be referred to as the central-cell diagram. It has three inputs and an output. The central cell's output must

be excited and remain excited when all three inputs have been excited simultaneously a certain number (usually random) of times.

The stimulus of the receptor neuron I_s is transmitted to the input I_s and that of the effector neuron to the input a_p; appearance of the sustenance excites the input N. If all three inputs are excited, the neuron P, which has a threshold of 2, and the neuron Q, which also has a threshold of 2, are excited. The excitation from the neuron Q is transmitted to the input of the excitation accumulator R.

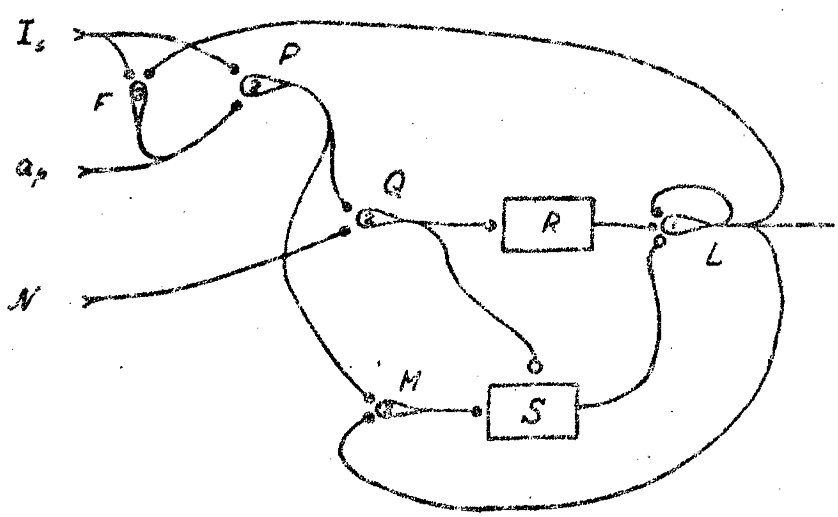


Fig. 2. Central cell.

Like all other neurons the accumulator R is also characterized by the accumulator threshold. However, this

threshold is a random value which depends on the number of foregoing excitations, on temperature, etc.

When the number of stimuli exceeds this threshold, the accumulator's output is excited. The accumulator axon has a terminal plate which is applied to the body of the neuron L, which has a threshold I.

The neuron L is excited, and due to the feedback loop, it remains excited. In addition to this, an inhibitory terminal plate is applied to the neuron L. Once having been excited, therefore, the neuron L remains excited until the inhibitory plate is excited. The reflex is developed. Now when the receptor neuron I_s is excited, the neuron F, which has a threshold of 2 (one of its plates, which is on the axon of the neuron L, is excited at all times) and is connected to the effector neuron a_p is stimulated.

Therefore when the stimulus I_s acts on the automaton, it will always respond with the activity a_p.

If, when this is done, the automaton does not receive the sustenance from the environment, a stimulus from the neuron P enters the stimulus counter S through the neuron M. The stimulus counter also has a definite threshold. If the situation recurs several times (the automaton does not obtain sustenance in response to the activity a_p), the number of stimuli will exceed the threshold of the

stimulation counter S, the counter's axon and, consequently, its inhibitory terminal plate, which is applied to the body of the neuron L, will be excited. The reflex is quenched.

If, however, the sustenance is received, then the neuron Q, whose axon is connected to throw the stimulus counter, is stimulated. The stimulus counter returns to its initial state. The reflex is reinforced and not quenched.

It is therefore possible to simulate a conditioned reflex by means of such a scheme. However, the medium is characterized by a certain set of stimuli. The automaton is likewise characterized by a certain set of reactions. It is necessary to enable the automaton to work out any conditioned reflex (any reaction to any stimulus).* This point has not been observed in any of the attempts to simulate the learning process. For this reason, as Kossa comments correctly in his book entitled "Cybernetics" /35/, the "turtle's" reflex was predetermined. The automaton must have "freedom to learn", i.e., the opportunity to select the necessary association from the set of admissible associations.

*We refer here to any of the reactions possible for the automaton, and to any stimulus sensed.

To solve this problem, let us construct a matrix m x n of central cells (Fig. 3). Each row of the matrix is

related to a definite effector neuron (i.e., a signal which stimulates the corresponding effector neuron a_k is delivered to the input a_k of each central cell forming the row of the matrix).

Each column of the matrix is associated with a definite receptor neuron. In addition to this, a sustenance signal is delivered to all central cells of the matrix.

If now, for example, the receptor neuron I_k is excited, the automaton responds with the action a_s, and the sustenance N is obtained, then all three inputs will be stimulated only at the central cell lying at the intersection of the k^{th} column and the s^{th} row. Only two or one of the inputs of all other cells will be stimulated. If the coincidence is repeated several times, then the neuron L is stimulated in this particular central cell and connects the axon of the k^{th} stimulus with the body of the s^{th} effector neuron through the neuron F. Thus we may develop any of the m x n possible conditioned reflexes.

For the reflex to be developed it is necessary that the automaton somehow act on the medium in which it is situated. For this purpose the automaton has a random-activity block which stimulates the effector neurons equiprobably. When the automaton has learned, the random-activity block is disconnected and the automaton responds in a definite manner to external stimuli.

c) The Problem of Differentiation of Time Representations

We have constructed the scheme of an automaton which simulates the development of a simple conditioned reflex. Let us pass now to the complex conditioned reflexes. Suppose the automaton must develop the chain of reflexes

$$I_2 - a_3 - I_1 - a_4 - I_5 - a_1 - N.$$

Then N will be the reinforcing factor for the association $I_5 - a_1$, I_5 will be this factor for the association $I_1 - a_4$, and N will be this factor for $I_2 - a_3 - I_1, I_5$. Since the automaton's learning process proceeds backward, the reinforcing factor for this reflex will be formed by all stimuli for which reflex responses have been developed previously. Consequently, we are confronted with the problem of distinguishing stimuli for which reflexes have been worked out.

The term time differentiation is used in the following sense: if some central cell (Fig. 3) has been simulated in the k^{th} column, then the stimulus I_k should become a reinforcing factor for all the remaining columns. If, further, some cell has been stimulated in the s^{th} column, then the stimulus I_s should become a reinforcing factor for all other columns with the exception of the k^{th}.

The problem of time differentiation reduces to the following: there exists a certain filament whose conductiv-

ity in the "all or nothing" sense controls a certain scheme with the numbered inputs 1 and 2. If the input 1 of this scheme has been stimulated earlier than input 2, then the filament conducts irrespective of whether input 2 is then excited or not. If, on the other hand, input 2 is stimulated earlier, the wire will not conduct regardless of whether input 1 is stimulated.

Let us consider the diagram of Fig. 4. A nerve filament, whose conductivity must be variable, forms the chain 3-4, into which the two neurons P and Q are connected. In its initial state, this circuit does not conduct stimuli, since the neuron Q has a threshold of 2. If the input 1 is now stimulated, the chain 3-4 will conduct, since one of the exciting plates at the neuron Q has been stimulated. Further, when the input 2 is stimulated the chain 3-4 will conduct, since the inhibitory plate at the neuron L is stimulated and the neuron will not be able to enter the excited state. On the appearance of a stimulus at the input 3, therefore, the neuron P is stimulated, and then the neuron Q, which already has one plate stimulated (threshold 2), and the excitation proceeds down the chain 3-4 in this manner.

Let us consider a case in which the input 2 is stimulated first. Then the neuron L will be excited and self-

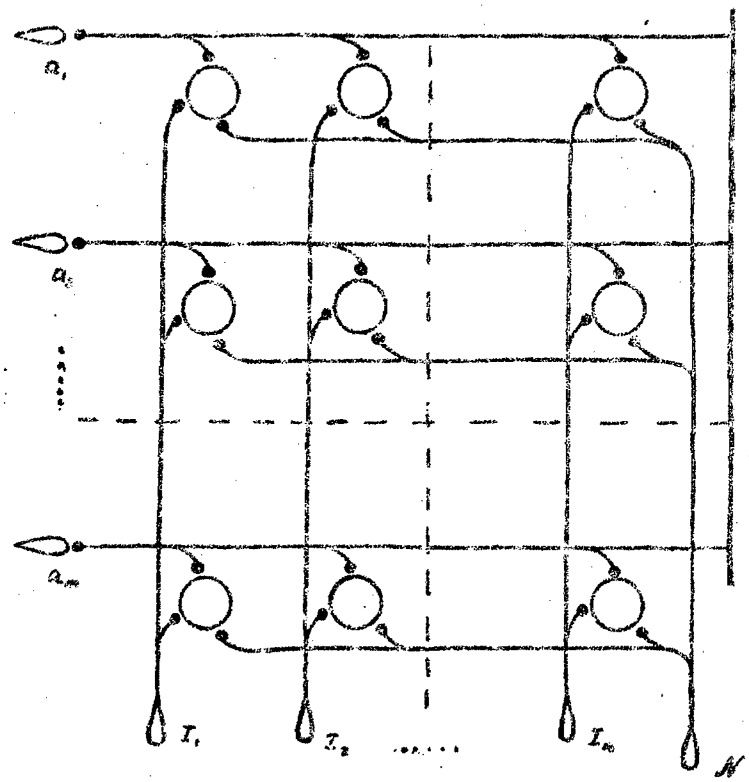


Fig. 3.

1) Random-activity block; 2) effector neurons; 3) receptor neurons.

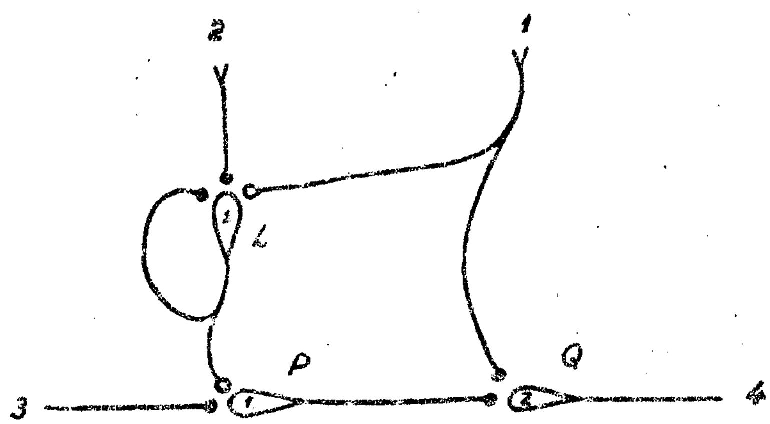


Fig. 4. Illustrating the problem of time differentiation.

locked by the feedback loop. The inhibiting plate at the neuron P will be excited and the chain 3-4 will be nonconductive. The neuron L has two excited exciting plates, and will not be inhibited by stimulation of the input I.

Thus we may solve the problem of time differentiation of stimuli.

d) Formal Scheme of Automaton

For the automaton to be able to develop conditioned-reflex chains (a program of activity), it is necessary to combine the network for the development of simple conditioned reflexes with the network for time differentiation of stimuli. Let us consider the complete diagram of the automaton.

Let us set up special reinforcement buses for each column and connect them through a scheme similar to that shown in Fig. 4 with each stimulus with the exception of the stimulus of the column in question. Figure 5 shows this connection for the column I_k. The terminal plates of the axons of all M central cells (their L neurons, see Fig. 2) of the column I_k are applied to the body of the neuron M_k. The terminal plates of the central cells of columns $I_1 \ldots I_n$ were applied to the body of the neurons $M_1 \ldots M_k$, respectively. Thus it is evident that all stimuli for which con-

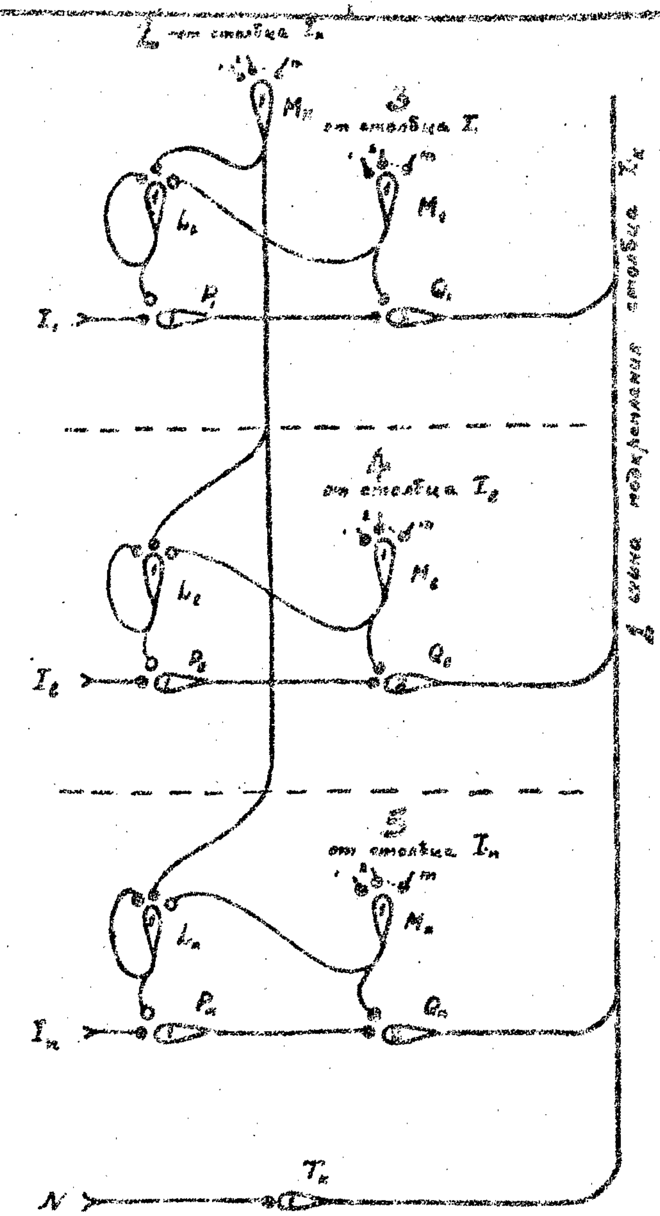


Fig. 5. Time-differentiation network

1) Reinforcement bus of column I_k; 2) from column I_k; 3) from column I_1; 4) from column I_1; 5) from column I_m.

ditioned reflex reactions were developed before any were developed for the stimulus I_k will become reinforcing factors for the conditioned response to the stimulus I_k. Those stimuli for which reflex responses were developed after the response to the stimulus I_s will no longer be reinforcing factors for the response to I_n. This occurs as a result of the operation of the system based on the neurons $P_1, Q, L, \ldots P_n, Q_n, L_n$, which we have already considered (Fig. 4).

Thus we have used formal neurons to construct an automaton circuit which simulates the development of a conditioned-reflex chain. The over-all block diagram is shown in Fig. 6. The work of its individual blocks has already been described.

The basic blocks of the automaton are the matrix of m x n central cells, n of the schemes presented in Fig. 5, and a random-activity generator block.

In the beginning, when the automaton has not learned it disturbs the environment at random as a result of the work of the random-activity generator. In turn, the environment reacts in some way on the automaton by exciting its receptor neurons $I_1, I_2, \ldots I_n$.

If a random coincidence of some stimulus I_s with an activity a results in the appearance of the reinforcing factor N, and this occurs several times, the association

in the automaton between the stimulus I_s and the activity a_k is strengthened (the central cell at the intersection of the s^{th} column and the k^{th} row is excited), and the automaton henceforth responds to the appearance of the stimulus I_s with the action a_k. If this reflex is not reinforced by the stimulus N it is eventually quenched. In addition to the establishment of the association between activity and stimulus, the stimulus I_s becomes a reinforcing factor for subsequent reflexes. This occurs as a result of the operation of the time-differentiation schemes 1,2,...n.

This continues until the reflex chain has been developed to the end. At this point the automaton is fully determined, i.e., it performs a definite activity in response to a definite stimulus.

If the external conditions have changed, the automat ceases to obtain sustenance as a result of its activities and proceeds to study. Then learning begins under the new external conditions in the same manner as described above.

There is a marked over-design in the structure of the automaton -- the matrix consists of m x n central cells, but when the automaton has finished learning, only m (or n) cells participate in the work. This excess is obviously necessary to escape the determinism which is characteristic

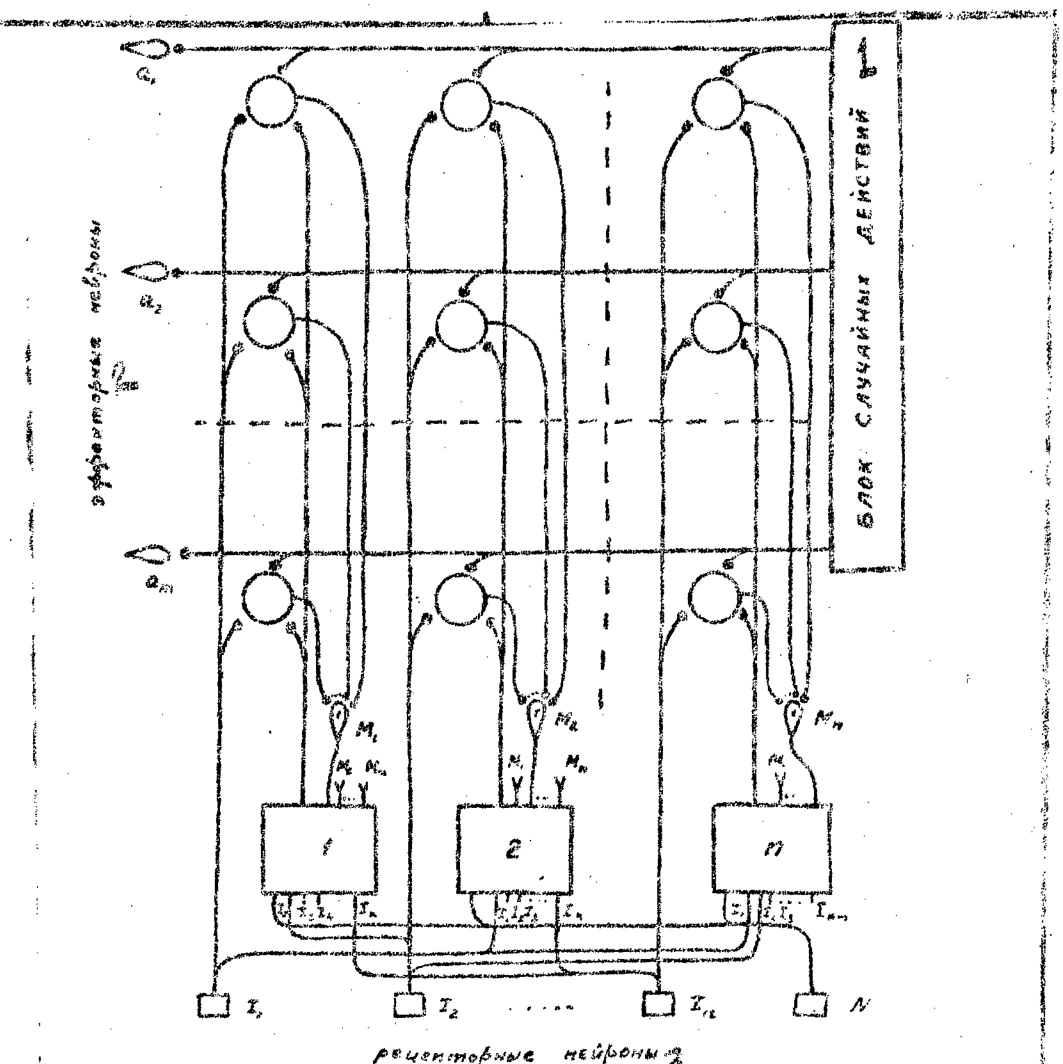


Fig. 6. Block diagram of automaton.

1) Random-activity block; 2) effector neurons; 3) receptor neurons.

of the "conditioned reflex" of the "turtle".

The block diagram of the automaton shown in Fig. 6 is somewhat simplified by comparison with the scheme of the actual automaton, but the two arrangements are similar in

principle.

The system of the automaton may be still further complicated so that it will produce a "reflex" not to a single stimulus, but to a certain combination of them. However, this would only result in quantitative complication of the scheme of the automaton.

Let us consider a subset of the set of stimuli. We shall denote the absence of a stimulus by "0".

$00 \ldots 0$ — subset 1 (vacant);

$I, 0, \ldots 0$ — subset 2;

$0, I_2, 0 \ldots 0$ — subset 3;

. . . .

$00 \ldots I_n$ — subset <u>n</u>;

$I_1, I_2 0 \ldots 0$ — subset $n + 1$;

. . . .

$I_1, I_2 \ldots I_n$ — subset 2^n.

There are a total of 2^n subsets in this set. Let us place a receptor neuron of the automaton in correspondence with each subset. Upon excitation of a given subset of the automaton's inputs, this and only this neuron should be excited.

Here we deal again with the activities of the automaton, and set a certain subset of activities into correspondence with each effector neuron. Then there will be 2^m

effector neurons. The matrix of the automaton is enlarged accordingly; it will contain $2^n \times 2^m$ central cells.

On the whole, an automaton complicated in this manner will be more general in nature, i.e., it will be capable of developing reflexes not only to isolated stimuli but also to a complex of stimuli. This stimulus complex will be sent by the automaton as some sort of whole which differs from the simple sum of the stimuli.

e) Certain Electrical Circuits of the Automaton

Let us now consider certain electrical circuits of an existing "learning" automaton.

The automaton was built at the Moscow Power Engineering Institute by the student design office for cybernetics, which is under the guidance of Yu.N. Kushelev*.

*G. Vaynshteyn, V. Borodnyuk, E. Letskiy, I. Glagolev, E. Ratgauz, and others took part in the design of the automaton.

Basically, the block diagram of the automaton is congruent with the block diagram constructed from the formal neurons, but somewhat more complicated in certain details. Thus, for example, a system was introduced to prevent the execution of two actions at once.

The automaton responds to four external stimuli. The stimuli are stimulated by pressing special buttons on

the automaton. The automaton can "perform" three activities, which are manifested in the lighting of one of three lamps. In addition, the automaton has three other special buttons, pressure on which simulates the appearance of the reinforcing factor.

The operative who pushes the buttons on the automaton takes the role of the environment in the learning process. The untaught automaton performs random activities, i.e., switches the lamps on and off at random. The automaton uses an original circuit in the random signal generator; this circuit employs the natural instability of operation of certain tube oscillators. The circuit was proposed by G. Vaynshteyn.

We shall not consider the entire schematic diagram of the automaton at this point. We shall consider only the circuits of the central cells and the time-differentiation network.

The schematic diagram of the central cells is presented in Fig. 7. As we see on examination of the circuits in Fig. 2 and Fig. 7, the neurons P and Q are realized by the coincidence circuits D_1, D_2, R_1 and D_3, D_4, R_2, respectively. The accumulator R and the neuron L are embodied in the capacitance C_1, which is charged from the voltage divider R_8R_9 through the resistance R_7 when the diode switch D_5 is

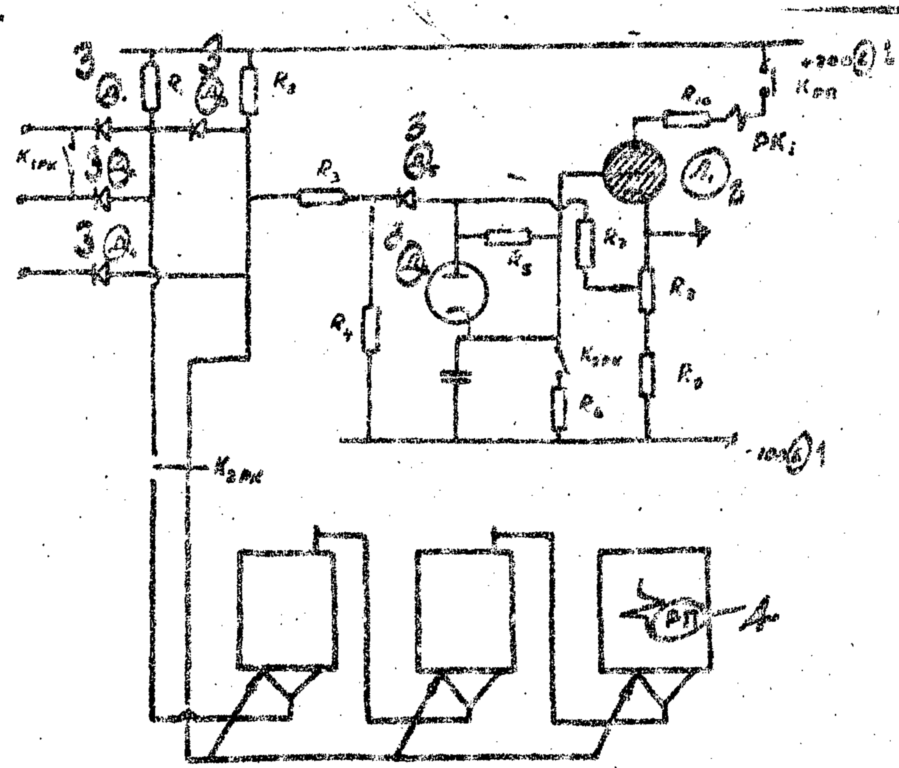


Fig. 7. Schematic diagram of simple cell.

1) Volts; 2) T_1; 3) diodes; 4) polarized relay.

open, and the thyratron T_1. The feedback loop of the neuron L is clearly not a part of the circuit, but the thyraton itself behaves similarly to the neuron with feedback loop, since once having been ignited, it will not be quenched as long as the plate voltate is applied. The thyratron's plate circuit contains the relay PK1, whose contacts form the neurons M and F. The excitation counter S is an ordinary trigger counter whose counting input is connected to the coincidence circuit $D_1D_2R_1$ and its clearing input to the coincidence circuit $D_3D_4R_2$. The polarized relay RP_1 is

placed in the plates of the last trigger of the counter with its contact in the plate circuit of the thyratron. The polarized relay is adjusted in such a way that when the counter is driven, the relay contact in the thyratron circuit is closed.

Let us describe the operation of the circuit in brief.

The lamp that simulates the activity of the automaton is lighted from the random-activity block and burns for about five seconds. During this time, a high voltage approximately equal to the plate-supply voltage appears at the input 1 of the coincidence circuit. When a stimulus button is pressed, a univibrator which gives a pulse approximately 5-10 seconds in duration is triggered. This pulse is fed to input 2. If the activity and stimulus pulses coincide in time, the high voltage also appears at point 4. If now a pulse is also delivered to input 3, the second coincidence circuit $D_3D_4R_2$ (the neuron Q) also operates, and the high voltage appears at point 5, opening the diode switch D_5. The capacitance C_1 begins to charge. The charging time constant of the capacitance is basically determined by the size of the resistance R_7 and the capacitance C_1. The voltage to which it is charged depends on the duration of the pulse. The capacitance is connected to the grid

of the thyratron T_1, so that when it is charged to a certain value, the thyratron is ignited. This will occur if the coincidence of all three voltages at the input 1, 2, and 3 recurs several times. The number of coincidences necessary depends on the frequency with which they follow one another, as well as on the values of the resistances $R_7 R_8 R_9$ and the quality of the capacitor C_1. Ignition of the thyratron signifies that the automaton has "memorized" the relationship between the corresponding stimulus and activity. The automaton's study proceeds in the manner described in the discussion of Fig. 2. The trigger counter counts the number of unsustained stimuli and when there are more than four (the counter counts up to four), the contact of the polarized relay in the thyratron circuit is opened and the thyratron goes out. Thus, the polarized-relay contact plays the part of the inhibitive terminal plate applied to the body of the neuron L.

The 3 x 4 matrix of the automaton (three activities, four stimuli) is constructed from twelve such circuits.

Let us pass now to consideration of the time-discrimination network circuit, which can also be termed the reinforcement block (Fig. 8).

The neurons $M_1 \ldots M_n$ (Fig. 5) are formed by the relays P_I, P_{II}, P_{III}, P_{IV}, and the contacts of the relays

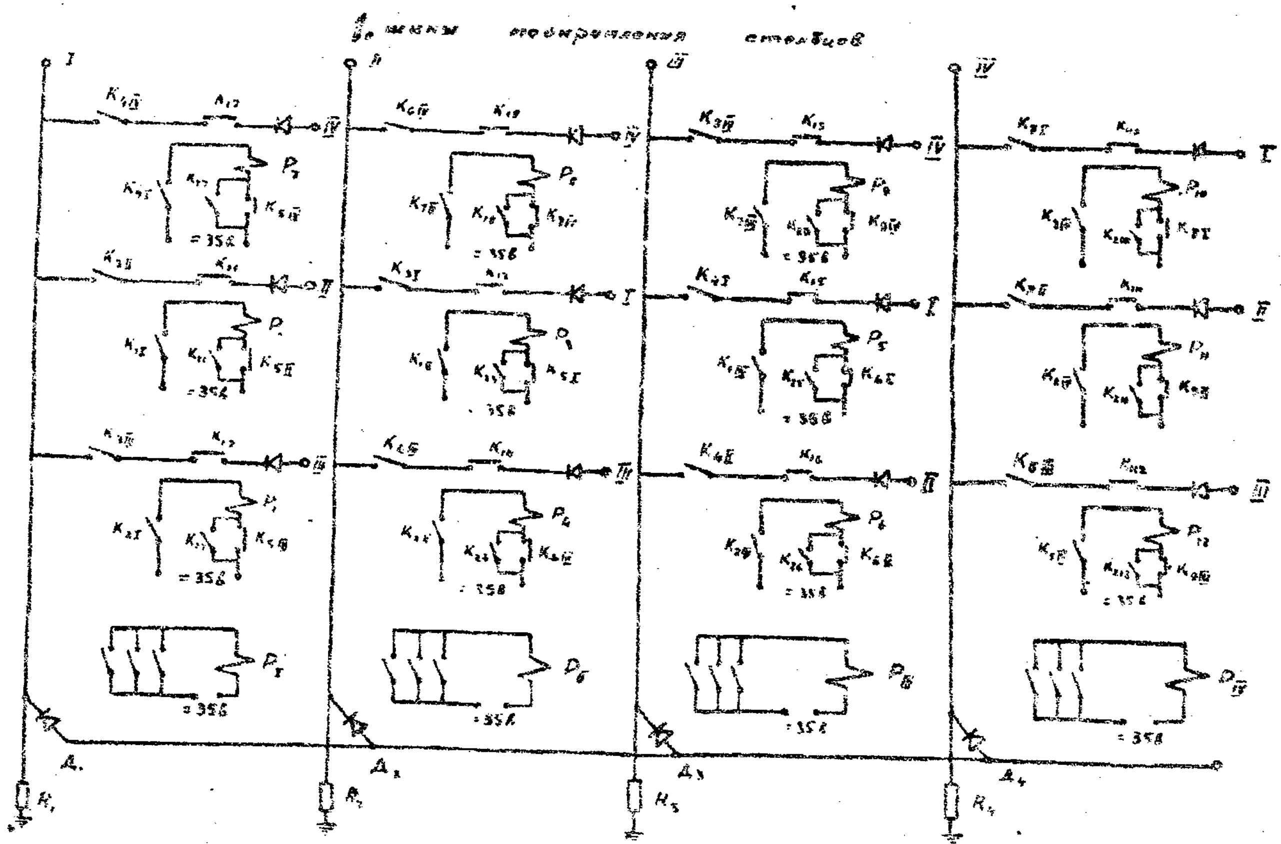


Fig. 8. Schematic diagram of time-differentiation network.

1) Reinforcement buses of columns. B — Volts; P — relay; K — switch; Д -- diode.

$PK_1 \ldots PK_{12}$ in the plate circuits of the thyratrons of the central cells. The contacts of these relays form an "or" circuit from each of the columns.

The contacts of the relays $P_I \ldots P_{IV}$, which are denoted by $Ki_I \ldots Ki_{IV}$ form the neurons $Q_1 \ldots Q_n$. The neurons $P_I \ldots P_n$ and $L_I \ldots L_n$ are formed by the contacts of the relays $P_I \ldots P_{IV}$, $PK_1 \ldots PK_{12}$, and the relays $P_1 \ldots P_{12}$ and thei contacts. Here, in this circuit, the feedback loop is clearly defined; it is formed by the contacts of the relays $P_1 \ldots P_{12}$ which hold automatically when they operate. The contacts which are shown open on the diagram are normally open and vice versa.

The neurons T_1 are embodied in the diodes $D_1 \ldots D_4$. This circuit works in exactly the same way as the formal-neuron circuit described earlier (Fig. 5).

As a whole, the automaton is an electronic computer containing approximately 100 tubes (including power supply), semiconductor diodes, and electromechanical relays.

The automaton described above is operational and is on exhibit at the Exposition of Attainments of the Popular Economy of the USSR.

f) Basic Features and Possible Applications of the "Learning Automaton"

Thus we have considered the circuit of a "learning automaton". What, if anything, new does it introduce into simulation of the learning process?

First of all, this automaton provides an opportunity for simulation of the conditioned reflex.* The automaton is capable of associating any of the motions of which it is capable with any of the stimuli that it senses. This possibility was not embodied in the models created earlier (Walter's turtle and others). The "central-cell matrix" is what makes this possible in this automaton.

Secondly, the automaton generates a chain of reflexes which develop in time in such a way that one reflex is followed by another. As far as we know, systems capable of such activity had not been created previously. Simulation of the development of a reflex chain leads to solution of the problem of distinguishing sequence in the appearance of stimuli (and fixing an association between stimulus and activity) in time.

Finally, simulation of the learning process in the automaton differs radically from simulation in electronic digital computers. The difference consists in the fact that

*See pages 56-58

the storage elements are conjoined with logical elements; this apparently approximates the singularities of the brain's structure in a certain sense.

The purpose of creating the automaton described her was to simulate physiological processes, but it may also have technical applications. An important property of the automaton consists in the fact that by "studying its environment" it works out a definite program of activity whic leads by the best route to the assigned goal under the specific conditions prevailing in the medium. By adapting it to a technological process concerning which little is known, therefore, it will by itself work out the optimum program of operation, with the quantity and quality of the resulting product playing the role of the "reinforcing factor". Little-understood processes are frequently encountered in the chemical industry, e.g., in the production of synthetic rubber. Under the supervision of Docent G.K. Krug at the Moscow Power Engineering Institute, research is being conducted on the application of a similar machine as an automatic dispatcher in the production of rubber.

The simulation of the learning process in automatic machines opens up prospects for the study of other problems.

In particular, resolution of the problem of learning in the automaton is of value for the creation of new

diagnostic machines which operate on the principle of the learning automaton.

In the opinion of Academician A.I. Berg, President of the Scientific Council on Cybernetics, and President of the Academy of Medical Sciences of the USSR Academician A.N. Bakulev, the creation of such automatons will open great prospects.

In addition to this, we encounter the problem of the possibility of more or less abstract mastery of a certain circle of objects possessing common properties, the problem of identification of a geometrical or auditory image, etc. The solution of these problems creates a prerequisite for understanding the activity of the brain in certain of its aspects. Apart from this, work on these problems will promote work in technology, where a number of such problems arise. However, they may be solved much more rapidly by studying the brain and simulating its functions in automatons.

CONCLUSION

The design and creation of a "learning automaton" has been of value in the study of two basic theoretical problems involving scientific analysis of the operation of the brain

The first problem may be characterized as the study of the general principles of operation of self-organizing control systems. In this case we speak of analysis of the complex phenomenon, which, in its general form, is characterized by the fact that the control system (the brain), using a certain series of actions, "investigates" its environment actively "with the purpose" of obtaining the necessary information. The result of this process is the detection of authentic and useful information on the basis of which new operating programs (new expedient behavior patterns) are formed. In characterizing this process in its general form, we deliberately avoid the use of the term "learning", since this term has recently become endowed with highly different significances.

The creation of a model of a "learning automaton" confirmed a number of hypotheses which had been advanced earlier on the basis of physiological experiments and concerned the principles and the mechanisms of the brain's operation, and revealed the erroneous nature of certain assumptions. Together with this, the creation of the automaton advanced a whole series of new problems and questions which indicate the necessity of further physiological investigations and determine the direction of these experiments.

The question as to the conditions under which a given algorithm employed by a control system may result in the formation of new operating programs is of particular interest, as are the conditions under which its use may prove ineffective.

Analysis of this problem points up the necessity of finding new algorithms which may prove optimum under a given set of conditions.

The second problem is related to analysis of the mechanism of operation of the brain, i.e., to analysis of the structure of the nerve network of the brain and study of the processes that unfold in this structure. This problem becomes particularly pressing in connection with the investigation of conditioned-reflex systems which indicate the existence of complex operating mechanisms in the brain. In this connection, we encounter the problem of studying the physiological mechanisms which provide for the sequential formation of complex reflex systems on the basis of processing of external information. This problem cannot be reduced to a problem of the mechanism of formation of a single reflex arc.

We have already spoken of the basic principles used in study of the operating mechanisms of the brain (Chapter I, Paragraph 4 of the present book). The development of the

nerve-network theory as applied to the problem of formation of conditioned-reflex chains and the realization of this theory through the construction of an automaton has as yet been unable to resolve the question as to the structure of the nerve network functioning in the brain. However, the creation of the automaton had important value for the study of this problem. In creating the automaton, certain general principles of the organization and work of nerve networks of this type were worked out.

Together with this, it was found possible to create working hypotheses concerning the physiological mechanisms at the basis of formation of reflex chains, which will serve as a basis for new physiological experiments. Further work in this direction will permit a more profound approach to the study of the brain's operation.

We have been able in the present volume to consider only a few of the problems which form the subject matter of neurocybernetics. For example, there arises an important problem that may be characterized as study of the ability of the brain to analyze complex external events (stimulus complexes). This problem is intimately related to the problem of classification of complex sets of signals. The number of various complex stimuli acting on the nervous system is extremely large. As a result, it appears that complex

processes of identification of common components in the various complexes are carried out in the course of the brain's activity, resulting in the formation of a unique system for the classification of complex stimuli. Each new phenomenon is sensed on the basis of detection in it of groups of signals which are already known to the animal. These phenomena, which apply very closely to the problem of concept formation, play a major role in orientation to new situations. A number of other problems also occur.

Neurocybernetics provides a new approach to the study of the work of the brain. In speaking of the value of cybernetics, E.Ya. Kol'man writes /34/: "To divine...the work of our brain and its very thought, to obtain ever-greater power to eliminate the disturbances and upheavals which arise in the processes of life — is this not really the high purpose the attainment of which is being approached by cybernetics in collaboration with biophysics, biochemistry, physics, and psychology? "

We may express confidence that this path of investigation can result in new progress in the fields of physiology and medicine, and prove to be of great assistance in the solution of the problem of complex automation of industrial processes.

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